ESA Contract 12536/97/I-HGE

End-to-end performance evaluation of SAR subsidence monitoring system

FINAL REPORT

Version 1

December 1998

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SUMMARY

This document represents the Final Report of a project entitled the ***End-to-end performance evaluation of SAR subsidence monitoring system,*** *ESA contract number 12536/97/I-HGE. The purpose of the project was to evaluate the performance of ERS SAR interferometry (InSAR) to meet the needs of those concerned with the mapping of subsidence, with the eventual aim of demonstrating a self-sustaining market for ERS InSAR products and the wherewithal for their provision.*

The project was conducted over a 12-month period with an initial allocation from ESA of 40 ERS SAR scenes for application to an intended 19 test-sites. Considerable effort was put into identifying sites of subsidence around the world and establishing reliable contacts for both ground-truth and possible commercialism. Data delivery delays and, in some cases, poor InSAR pair availability led to the necessity for 'multi-epoch' processing over most sites. Because of this, the data allocation was increased in mid-term to 80 scenes. Processing throughput was also faster than anticipated, with each product taking on average 47 hours to generate from RAW SAR data to final map layout.

39 InSAR products were generated for a total of 26 test-sites (>1 dataset per site). Useful and quantitative subsidence map products were generated for 18 (69%) of the 26 test-sites. 18 of the 26 test-sites were in the Southwest United States (Houston and Mexico City included) and positive results were generated for 13 (72%) of these. All graphical output is contained in the separate Appendix, together with individual test-site and processing information.

The bias in application towards the SWUS and the corresponding success rate in InSAR processing is indicative of the insidious and ubiquitous subsidence prevailing in the region, caused largely by the overdrafting of groundwater. It also demonstrates the operational match between the arid, coherence-stable landscape of the region, the capabilities of ERS InSAR and availability of appropriate SAR data.

The project has demonstrated an undeniable market for ERS InSAR products in the SWUS. The work has also resulted in an impressive and unique portfolio of case-studies that show reliability. These have been used extensively to establish an influential network of contacts in State Water Resource Departments, subsidence-control organisations, the USGS and other potential markets. Modest sales have already begun as a direct result of the work.

The project revealed and has quantified a variety of inefficiencies that serve to act as obstacles to the commercialism of ERS InSAR, the most significant at the moment being SAR data access and availability. The work identifies a number of archive and distribution processes that might benefit from a re-assessment of objectives, as the technical capability is clearly demonstrated. As requested, recommendations are made.

The authors of this work would like to give credit to all those that have given support to the project. In particular:

Andy Smith *of Phoenix Systems, Surrey.*
Michael Carpenter *of the USGS Water Resources Department, University of Arizona, Tucson, Arizona.*
Devin Galloway *of the USGS, Menlo Park, California.*
Maurice Tatlow *of the Arizona Department of Water Resource, Phoenix, Arizona.*
Donald Helm *of the Department of Engineering, Morgan State University, Maryland.*
Guy Duchossois, Livio Marelli *and* ***Mark Doherty*** *of ESA HQ, Paris and ESA-ESRIN, Frascati.*
Staff of the Data Order Desk*: ESRIN, Frascati.*

Ren Capes, Mark Haynes and Geraint Cooksley: NPA, Edenbridge, December 1998.

CONTENTS

1: INTRODUCTION

This document represents the Final Report of a 12 month project entitled *End-to-end performance evaluation of SAR subsidence monitoring system*, ESA contract number 12536/97/I-HGE.

The Report assumes the reader is familiar with ERS SAR, the InSAR technique in general, ESA-ESRIN systems, and has read the *Project Strategy and Quality Analysis Plan* produced by NPA in January 1998.

The phrase *ERS InSAR* is used in this document to imply not just the technical and operational aspects of the SAR instrument and ERS platform, but also the whole path from mission control, through ground reception, to ESRIN data management and dissemination. ERS InSAR also implies the basic characteristics of the interferometric products that can be generated using ERS-1/2 data.

The Final Report falls into five broad parts. Sections 1 to 3 provide background to the project and the subsidence map market. Sections 4 to 7 discuss the test-sites chosen and the acquisition and processing of data. Sections 8 and 9 describe the markets engaged and the corresponding promotional activity. Sections 10 and 11 then go on to discuss the realised commercial potential for ERS InSAR, and provide some recommendations to help see it realised, with final concluding remarks in section 12.

2: PROJECT OVERVIEW

2.1: Objectives

The purpose of the project was to evaluate the performance of ERS InSAR to meet the needs of those concerned with the mapping of subsidence, with the eventual aim of demonstrating a self-sustaining market for ERS InSAR products and the wherewithal for their provision.

In accordance with ESA's original Statement of Work (ESA D-/APP-RS-PM, 10.10.97), the primary objective of the project was to provide a comprehensive and quantitative quality analysis, representative of the needs of a focused end-user market segment, the ultimate goal being to enable ESA to adapt its present EO services towards specific market needs and opportunities.

This can be broken down into two secondary objectives:

- Determine the commercial potential for ERS InSAR subsidence maps.
- Assist the kick-starting of such a market if shown to be viable.

The objectives were to be met by:

- Analysing the markets for subsidence maps.
- Determining how ERS InSAR can satisfying such markets.
- Developing a marketing strategy to commercially deliver the ERS capability.

2.2: Overview of work performed

To guide the work an initial strategy was developed with a particular focus on the UK insurance and risk management sectors, though all potential subsidence map markets were to be considered in any part of the world for which appropriate ERS SAR data was available (*Project Strategy and Quality Analysis Plan*, NPA, January 1988). The project was conducted over a 12-month period with an initial allocation from ESA of 40 ERS SAR scenes for application to an intended 19 test-sites. The data allocation was subsequently increased to 80 scenes to allow for the realised necessity to process InSAR pairs for more than one epoch (temporal separation) for most sites.

Work commenced with the identification of sites known to be subsiding around the world. For each site it was necessary to establish (preferably commercial) contacts with a concern for the prevailing subsidence in efforts to acquire the necessary ground-truth for validation, and as potential customers to whom future sales might be made. To induce contacts to participate, the promise was made (and kept) to share the results of the interferometric processing by way of hard and softcopy and interpretation in return for ground-truth results. Test-sites were not pursued where no such contact could be established. The identification of sites and contacts in fact continued throughout most of the project.

As test-sites were chosen for processing, ERS SAR data pairs were identified from ESA's DESCW and FRINGE database and RAW data ordered from the ESRIN Order Desk. DEMs were sourced for the sites as necessary for the differential DEM-elimination process employed by NPA. Data pairs in temporal correspondence with the known ground-truth were identified with the minimum perpendicular baseline (Bperp) available. Besides reducing errors due to inadequate DEM accuracy, this allowed useful results to be produced in the instances where no DEM was available and only non-differential interferograms could be generated.

Subsidence maps were generated by SAR processing the RAW ERS data to SLC, interferometric processing and then standard image processing techniques to produce map layouts and visualisations. Not all datasets resulted in positive (useful) output. Those that did were sent to the contacts concerned with the site, who were then followed-up for their feedback and in the hope of contracting further work. It was accepted that some commercial risk was associated with the 'free' dissemination of output, but this was balanced against the need to induce effort on behalf of the contacts to provide ground-truth and the need to stimulate interest in a product unfamiliar to what can be conservative markets. Also, results were derived from archive data so that any contemporary measurement of subsidence by this technique was still outstanding. Notwithstanding, all efforts were to be made during the project term to make commercial sales of the InSAR subsidence map products generated, whereby NPA would pay ESA the commercial rate for the ERS SAR data involved, the data allocation then being increased correspondingly.

The project originally cited UK risk management and insurance as a prime target for InSAR-derived subsidence maps because of the high claim rate against clay shrink-swell induced building damage. This application was, however, found to be outside the spatial resolution capability of ERS InSAR. The market discovered as having most potential was the Southwest United States (SWUS), where subsidence in semi-arid regions is ubiquitous due to groundwater abstraction, the dry landscape is 'coherence-stable', and funds are available to pay for subsidence information products.

3: THE MARKET FOR SUBSIDENCE MAPS

Subsidence, or the sinking of the land surface, is widespread around the world and causes expensive damage to property and development. Usually the process is slow, invisible and insidious. Rarely is there a single dramatic event at the outset to warn of impending catastrophe. Subsidence, and its effects, may go unnoticed for months or even years until new and precise levelling takes place or underground pipelines crack, oil rigs fail, flood waters inundate or canals no longer carry original design flows, by which time remediation is often expensive.

Subsidence around the world is increasing. Population growth, accelerated exploitation of natural resources and the possibility of climate change all make subsidence more probable. Building continues over known regions of seismic activity, increasing volumes of water and oil are abstracted which depletes underground cavities of their support, and changes in rainfall distribution may have drastic effects on building foundations. World-wide, major areas of subsidence have developed over the last 50 years due to the rapidly increasing uptake of groundwater, oil and gas - the most common form of subsidence globally. It is unlikely in the foreseeable future that the causes of this type of subsidence will decline, and so economic methods to monitor and measure the effects become desirable.

3.1: Market sectors

The following lists the main market categories for subsidence maps (for more detail, refer to the *Project Strategy and Quality Analysis Plan*). Due to the significance of the SWUS, this region and its associated markets are described separately in section 3.2.

- **Insurance industry**: Claims against subsidence damage are significant and cause and effects are poorly understood, *e.g.* London clay shrink-swell.
- **Risk management consultancies**: As providers of quantitative risk models to the insurance industry, there is a demand for subsidence information products, *e.g.* London clay shrink-swell.
- **Civil engineers**: Responsible for site analyses and sometimes ongoing monitoring of structures, *e.g.* Channel Tunnel Rail Link, UK.
- **Oil and gas companies**: Depletion of reservoirs can cause stratigraphic collapse, damaging rig equipment and reducing production, *e.g.* Belridge, CA.
- **Mining authorities and companies**: Many have legal obligations to monitor and control the subsidence they may cause, but often have no practical means of doing so, e.*g.* Selby Coalfields, UK.
- **Legal profession**: Lawyers may become involved in litigation involving claims against others who may have caused subsidence resulting in property damage, *e.g.* groundwater abstraction causing subsidence damage in Las Vegas, NV.
- **Environmental pressure groups**: May require subsidence information products as evidence against those causing subsidence.
- **Local Government Authorities**: May have overall concern for subsidence occurring within their jurisdiction, *e.g.* Tucson City Hall, AZ.
- **Water resource authorities**: Concern for environmental damage caused by increasing volumes of water abstraction, *e.g.* Arizona Department of Water Resources.
- **Specific subsidence monitoring organisations**: Organisations set-up specifically by government to monitor regions of significant known subsidence, *e.g.* Harris-Galveston Coastal Subsidence District, TX.

- **Geological Surveys**: Overall interest and sometimes official obligation to monitor and oversee control, *e.g.* USGS.

3.2: Subsidence in the USA

3.2.1: Background

More than 44,000km^2 of land in 45 states in the US has been lowered by various forms of subsidence in the last 100 years[1]. Underground mining of coal (8,000km^2), groundwater abstraction from underground aquifers (26,000km^2) and drainage of organic soils (9,400km^2) are the principle causes. In addition about 18% of the conterminous US is underlain by cavernous limestone, gypsum, salt or marble and is locally susceptible to catastrophic collapse into sinkholes.

Annual costs from resulting flooding and structural damage exceed 125 million USD. Although these costs are small relative to those of many other earth-science hazards, their geographic distribution is not uniform. Thus localised areas bear disproportionate shares of these costs. In addition, parties damaged by subsidence associated with resource removal commonly are obstructed from reimbursement by legal recovery systems that are in conflict with doctrines that establish rights to resource removal.

Table 1: Estimated annual losses in 1977 caused by some types of subsidence in the US.

Subsidence type	**Millions USD**
Mines	30
Sinkholes	10
Underground fluid abstraction (oil and water)	**35**
Natural compaction	10
Organic soils	40

Fortunately, subsidence is more hazardous to property than to life because of the typically slow rates of lowering. It has caused few casualties. Subsidence however increases the potential for loss of life in flood-prone areas by increasing the depth and size of areas susceptible to inundation.

3.2.2: Subsidence caused by groundwater abstraction

The desert climate of much of the SWUS affects economy and quality of life. Most economic activity, including mining, irrigated agriculture and growth of cities, occurs only where dependable water supplies are available. There are three sources of water: surface (lakes, rivers and streams), reclaimed (a growing resource from recycled effluent) and groundwater. The existence of groundwater allows geographic independence from surface water supplies and demand has dramatically increased this century, particularly since the invention of the turbine pump, and now accounts for 40% of total water usage. Growing demand means that abstraction from these aquifers is occurring at rates faster than replenishment, creating conditions known as 'overdraft'.

Fluids underground are often in place for millions of years and the weight of the overburden above is supported by both fluid pressures and stresses transmitted through the solid skeleton of the reservoir soil or rock. In conditions of overdraft, fluid pressures decline and support of the overburden is transferred to the solid skeleton. If the reservoir soil or rock is compressible, large and permanent loss

[1] Committee on Ground Failure Hazards Mitigation Research (1991) *Mitigating Losses from land Subsidence in the United States.* National Academy Press, Washington D.C.

of pore volume or compaction will occur as it adjusts to the new stresses, and depending upon local geology, lead to an expression of large-scale subsidence at the ground surface sometimes covering many tens of square kilometres at low gradients. Though the phenomenon is realised by the appearance of fissures, structural damage and sometimes flooding, the extent and rate of subsidence has proved extremely difficult, if not practically impossible, to measure by conventional means.

More than 31 areas in 7 states have subsided in this way. The two largest are in the San Joaquin Valley, CA and Houston, TX where 13,500km^2 and 12,000km^2 respectively have subsided. Maximum elevation loss has been 9m in ~50 years in the San Joaquin Valley (see Figures 1 below and 2 overleaf)

Figure 1: Map of costs

National distribution of subsidence caused by fluid abstraction by state. Costs were compiled from published and unpublished sources for the purposes of providing an order-of-magnitude, state-by-state comparison. Only relative importance is suggested as the time periods on which estimates were based vary by state, and costs were not converted to constant dollars. In general, costs are conservative estimates.

Source: Committee on Ground Failure Hazards Mitigation Research (1991) *Mitigating Losses from land Subsidence in the United States*. National Academy Press, Washington D.C.

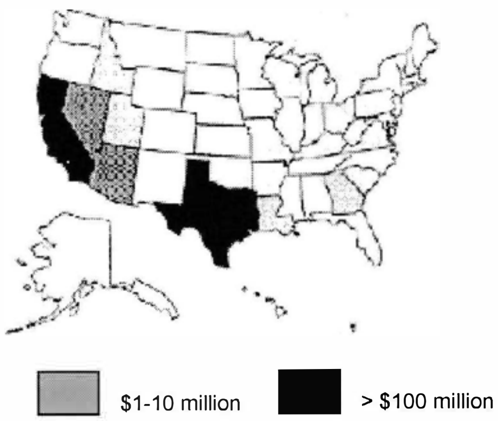
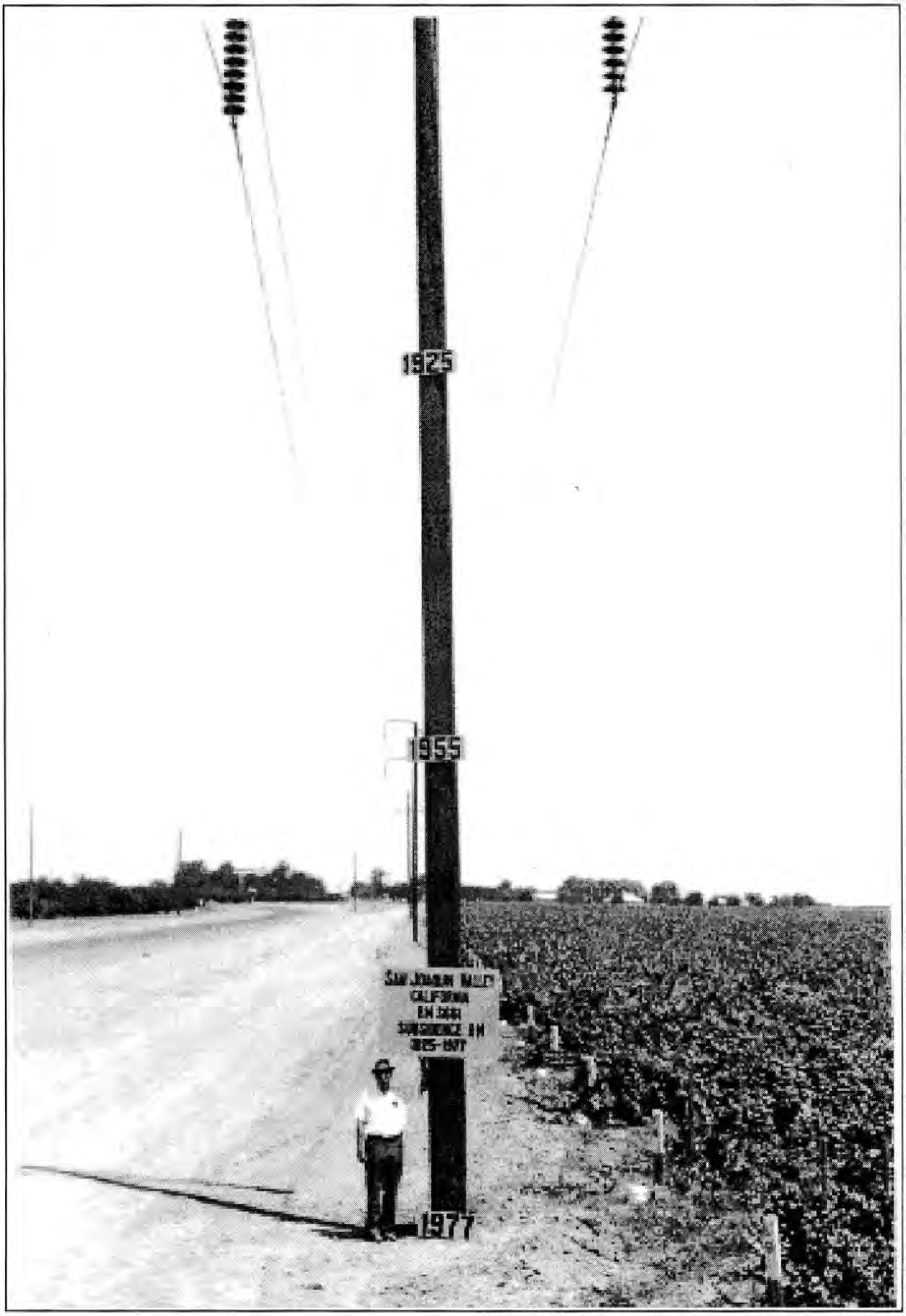


Figure 2: Approximate location of maximum subsidence in the US caused by groundwater abstraction. Point is west of Mendota, CA. Subsidence of 9m occurred from 1925 to 1977.



3.2.3: The need to map and monitor subsidence

Besides flooding, subsidence in built environments can cause severe damage, often insidious in nature, only being discovered once remediation becomes expensive. The problem is worsening as rates of groundwater and oil abstraction increase with growing population and economic activity. There is therefore an economic interest to map and monitor subsidence to:

- identify areas and structures at risk for planning and control,
- map rates of displacement against abstraction,
- verify claims for damage, and
- validate remedial action.

The types of information required include:

- 3D location and volume of aquifers.
- Location and volume of abstraction activity.
- Geology and topography.
- Coincidence with anthropogenic surface features of concern (*e.g.* towns, canals, railways, agriculture and irrigation systems, airports, utility installations).
- Location and geographic extent of subsidence.
- Rates of subsidence (± 1cm/y).

The first four types of information are available from existing sources. The last two are practically impossible to obtain by conventional means except at coarse and irregular resolution.

ERS InSAR has the capability to locate the geographic extents of subsidence that has occurred between two dates to within centimetres, particularly in the SWUS where the arid, semi-desert landscape is *coherence-stable*, allowing the generation of interferograms with temporal separations spanning several years. For the first time, subsidence maps at say 100m continuous resolution over 10,000km^2 at a time can be produced. Not only is the information broader and of much higher resolution, but the cost to risk managers of an ERS InSAR subsidence map is a fraction of that to monitor one single point by extensometer. The Arizona Department of Water Resources in conjunction with the US Geological Survey has six extensometers located at various points around the town of Tucson. Though very accurate (± 1mm), their deployment has cost more than half a million dollars in hardware alone. Further, ERS InSAR results have shown their deployment to be away from the main subsidence event.

4: TEST-SITE IDENTIFICATION

4.1: Sources of information

A variety of methods and sources were used to identify potential test-sites:

- Proceedings of the International Symposium on Land subsidence 1995, 1991 & 1984 (best one stop source.
- Mailshots to attendees of the Fifth International Symposium on Land subsidence, and world geological surveys.
- The Proceedings of the USGS Subsidence Interest Group Conference, Las Vegas, 1995 & Antelope Valley, 1992.
- Literature search at the Geology Society and British Library.
- USGS: Stanley Leake's Land Subsidence From Ground-Water Pumping – which listed Eloy, Phoenix, Tucson, Las Vegas, Albuquerque, Mimbres Basin, Lancaster, Mendota, Davis, Ventura, El Paso, Houston
- USGS Water resources home page
- USGS Ask a Geologist service: can leave an enquiry on the internet site that will be emailed to geologists who then reply.
- Telephone enquiries (Institute of Hydrology, Wallingford, UK and British Geological Survey
- Contacts made through personal meetings (REC in Tucson, NP in Salt Lake City)

4.2: Criteria for test-site selection

- **SAR data access:** Sites would not have been considered if only within the footprint of the Hyderabad PAF due to the nigh impossibility of extracting data from them within reasonable time-frames.
- **Commercial potential:** There needed to be a potential for economic damage, so test-sites were primarily urban. Built environments also have the advantage of coherence-stability.
- **Economy of country involved:** A rich country is more likely to pay for subsidence information than a poor one, so priority was given largely to subsidence in the western world, and particularly the USA.
- **Nature of subsidence:** All types of subsidence were open for consideration except sinkholes caused by dissolution. Though effects can be catastrophic, they tend to be localised and beyond the spatial resolution of ERS InSAR, *e.g.* deformation and collapse caused by gypsum dissolution in Ripon, North Yorkshire, UK. In general, subsidence needed to be continuous in nature and more than half a square km in areal extent to allow for pixel averaging, *e.g.* resulting pixel size of 100m x 100m.
- **Rate of subsidence:** To reduce ambiguity, an interferogram should contain complete fringes which can be shown to be developing or increasing in number by processing data of different temporal separations. Therefore, more than a few centimetres of subsidence should have occurred within a period, the length of which is determined by the coherence-stability of the landcover and the SAR data archive. If the archive allows, interferograms can be stacked to sum <1 fringe displacements.
- **Land cover:** If targets were non-urban, then rates of subsidence had to be considered against landcover and coherence-stability. For example, sufficient coherence just persists over a winter 35-day pair to map the fast displacements associated with active coal mining under the rural landcover of northern England (<9cm). However, the arid and rocky non-urban environment surrounding Tucson can be mapped using temporal separations spanning the many years needed to detect the much slower rates of displacement (sometimes mm/year).
- **Ground-truth:** To decide on data for processing, the project needed to know where the subsidence was occurring, over what period(s) and by how much.

4.3: Ground-truth

The identification of sites around the world suffering the effects of subsidence is not difficult, as illustrated by the numerous sources of information shown above. The difficulty is obtaining the quantitative ground-truth necessary.

- The location of displacement.
- The amount of displacement.
- The rate of displacement.
- The absolute period(s) of displacement.

This information is fundamental to enable specification of the 'epoch' over which measurements should be made, *i.e.* the appropriate acquisition dates and temporal separation of an InSAR pair. In many cases there is no conventional means to measure large-scale subsidence, which is indicative of the unique attributes and marketability of ERS InSAR.

It must be stressed that the quality of ground-truth obtained for the project varied widely, from no quantitative information at all, in which case the site would not be pursued, to reliable, dated subsidence contours, *e.g.* subsidence maps prepared by the Harris Galveston Coastal Subsidence District. Another problem was the long delays sometimes experienced in receiving the ground-truth, preventing the specification and ordering of data until late into the project.

This difficulty is compounded by the availability of appropriate InSAR pairs. It is the exception where quantitative ground-truth is known and a dataset exists that ideally 'brackets' the event. Sometimes a 'two shot' approach is required choosing one pair with a long temporal separation, say 3 years, guaranteed to bracket an event but where poorer coherence might prevent fringe-generation, and then another pair of shorter separation, say 1 year, to counter problems of poorer coherence but where the amount of displacement might be less or even outside the displacement resolution of the system. Often, an informed judgement has to be made as to which, or how many ERS datasets should be processed.

4.4: Test-Site Identification Report

The details relating to all test-sites considered were recorded in *Test-site Identification Reports*. Each test-site was given its own ranked record. Ranking was decided by team discussion on the following test-site attributes:

1. **Marketability**: Commercial potential.
2. **Subsidence category**.
3. **Geographical extents and optimal ERS coverage**: Lat/long and extents and dimensions in km of subsidence and/or urban site, together with corresponding (DESCW) graphic of most suitable ERS frame(s).
4. **Socio-economic effects of subsidence**: Impact on local population and associated costs.
5. **Customer/contact**: Possible end-users and/or source of ground-truth.
6. **Subsidence rate/amount**: Known, quantified subsidence details.
7. **Ground truth availability**: Ground-truth that was available and/or could be obtained.
8. **Land cover**: Nature of ground surface/cover which affects temporal choice of interferometric pairs.
9. **ERS data availability status**: The statistical temporal specifications of suitable interferometric pairs in archive within certain criteria, *e.g.* Bperp $\leq$ 50m and temporal separation $\geq$ 1 year, plus scene order/receipt status.
10. **DEM availability**: Alternative options/sources of DEMs, held in-house or acquired.
11. **Processing status**: Stage of data processing reached.

Each test-site considered was assigned a rating percentage to provide a quick, quantitative means of evaluating its relative ranking against other sites, plus its suitability for short-listing and subsequent data ordering and processing. These reports appear with each processed result in the Appendix. The reports for sites considered but not pursued are also shown in the Appendix.

4.5: Test-site summary

In total, 31 test-sites were considered, of which 26 went forward for processing (NPA was contracted to process 19 test-sites, the extra 7 were enabled by a faster than anticipated rate of processing and ESA's increase in data allocation from 40 to 80 scenes). Tables 2, 3 and 4 list all the test-sites considered. Table 2 lists all those processed in the SWUS plus Houston and Mexico City - 18 sites in total. Table 3 lists the 8 remaining sites processed. The graphical results of the processing for these 26 sites, along with interpretations and the corresponding Test-Site Identification Reports, are provided in the Appendix. Table 4 lists sites considered but not processed (5 sites). Each table is sorted by *% rating* (derived from the combined ranking in the 5 preceding columns). Test-sites in bold indicate positive (useful) results. Geographic distribution is shown in Figures 3 and 4 overleaf.

Table 2: Test-sites processed in the SWUS, plus Houston and Mexico City

	Test-site	Market.	Rates / Amount	Ground-truth	Cover	Data	% rating	Tsep	Bperp
1	**Las Vegas Valley 1**	2	2	2	3	3	80	3yrs	30 m
	Las Vegas Valley 2	2	2	2	3	3	80	1yr 1m	45 m
6	**Houston 1**	3	2	3	2	1	73	1yr 2m	89 m
	Houston 2 (not proc.)	3	2	3	2	1	73	2yrs 2m	91m
	Houston 3 (not proc.)	3	2	3	2	1	73	3yrs 8m	22m
2	**Los Angeles**	2	2	1	3	3	73	2yrs 2m	55 m
11	**Mimbres Basin**	2	1	1	3	2	73	2yrs	38m
3	**Phoenix 1**	3	1	1	3	3	73	1yr 1m	32 m
	Phoenix 2	3	1	1	3	3	73	3yrs 4m	6 m
4	Tombstone 1	2	2	1	3	3	73	2yrs 11m	31 m
	Tombstone 2	2	2	1	3	3	73	1yr 2m	48 m
8	**Tucson 1**	3	1	2	3	2	73	1yr 1m	2 m
	Tucson 2	3	1	2	3	2	73	3yrs 9m	1 m
5	**Eloy-Picacho 1**	2	1	2	3	2	67	1yr 1m	29m
	Eloy-Picacho 2	2	1	2	3	2	67	2yrs 3m	42m
7	**Lancaster 1**	2	1	1	3	3	67	1yr 2m	55m
9	Bingham	2	1	1	2	3	60	11m	16m
10	Bingham & SLC	2	1	1	2	3	60	1yr 1m	11m
17	**Mexico City**	2	2	1	3	1	60	1yr 3m	70 m
12	**Reno**	2	1	1	2	3	60	1yr 11m	64m
13	**Ventura 1**	2	1	2	1	3	60	1yr	84m
	Ventura 2	2	1	2	1	3	60	1yr 11m	25m
	Ventura 3	2	1	2	1	3	60	3yrs 1m	16m
14	Albuquerque	2	1	1	2	2	53	2yr	48m
15	**Davis**	2	1	1	2	2	53	2yr	26m
16	El Paso	2	1	1	2	2	53	1yr 10m	29m
	Lancaster 2	2	1	1	1	3	53	3yrs 1m	127m
18	**SW Mendota 1**	2	1	1	1	3	53	1yr 11m	27m
	SW Mendota 2	2	1	1	1	3	53	3yrs	23m

Figure 3: Geographic distribution of US test-sites considered and processed

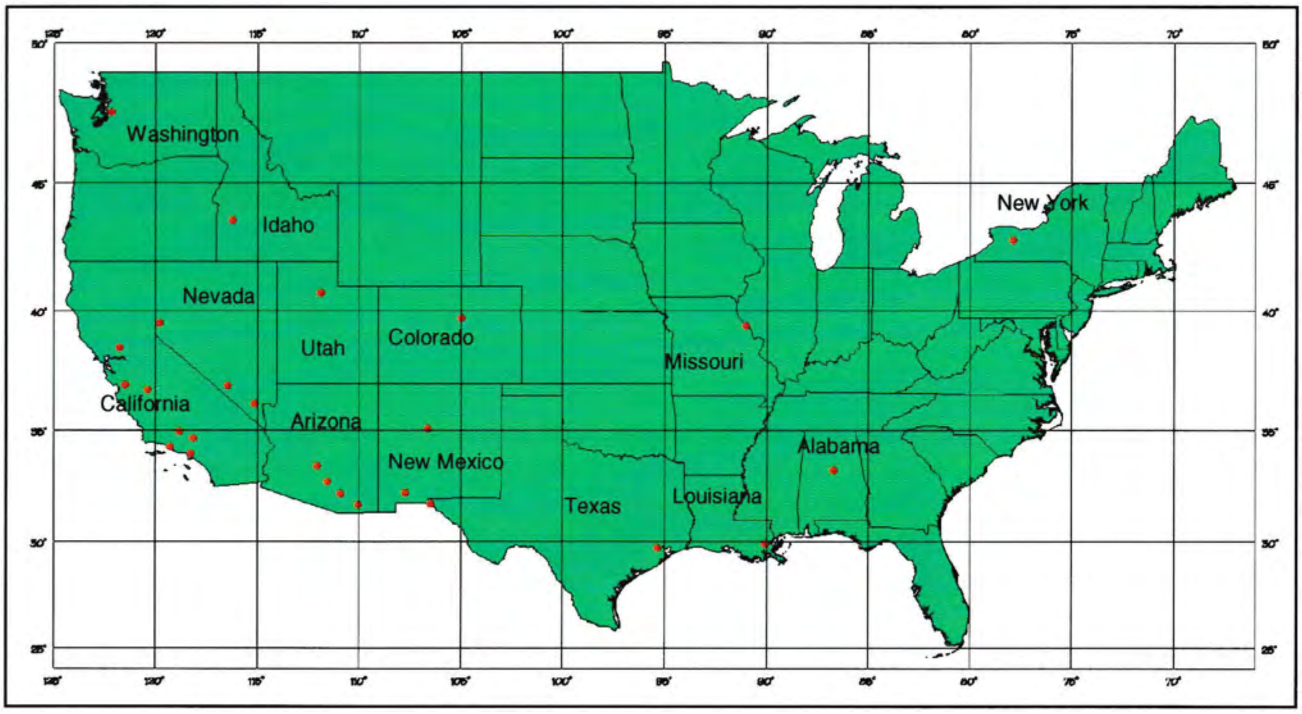


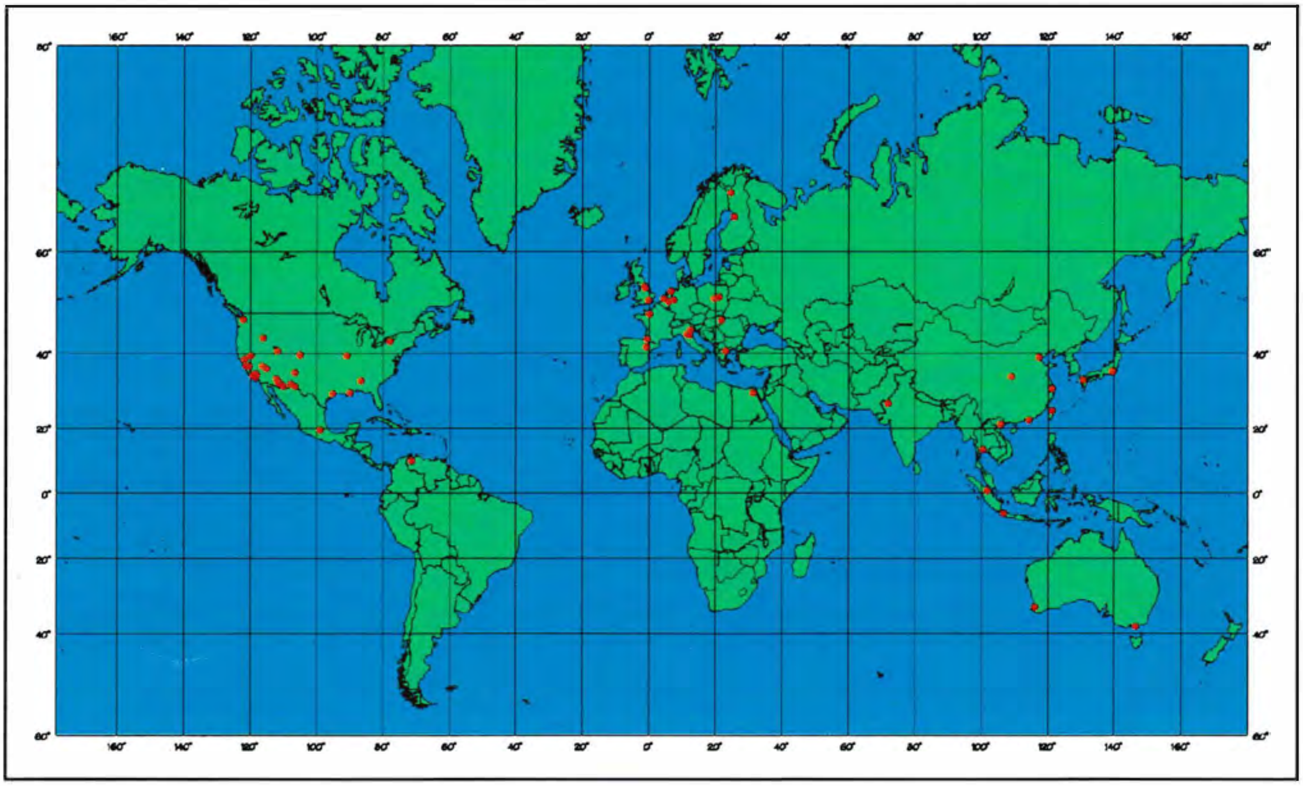
Table 3: Non-SWUS test-sites processed

	Test-site	Market.	Rates / Amount	Ground-truth	Cover	Data	% rating	Tsep	Bperp
20	**Japan, Kanto Basin**	3	3	1	3	1	73	2yrs 7m	10 m
19	**Australia, Latrobe**	2	1	1	1	3	53	3yrs	119m
21	Netherlands, Rotterdam	2	1	2	3	3	73	3yrs	134m
22	**Italy, Bologna 1**	2	2	2	2	3	73	1yr	14m
	Italy, Bologna 2	2	2	2	2	3	73	2yrs 3m	75m
23	Italy, Ravenna	2	1	2	2	3	67	1yr	66m
24	Thailand, Bangkok 1	2	2	2	2	1	60	2yrs 6m	172 m
	Thailand, Bangkok 2	2	2	2	2	1	60	8m	23 m
25	**UK, London 1**	3	1	1	3	3	73	1day	188 m
	UK, London 2	3	1	1	3	3	73	6m	6m
26	**UK, Selby 1**	2	3	2	1	2	67	2m	191 m
	Uk, Selby 2	2	3	2	1	2	67	1m	200 m

Table 4: Test-sites seriously considered, but not processed

	Test-site	Market.	Rates / Amount	Ground-truth	Cover	Data	% rating	Tsep	Bperp
27	US, Denver Landslide	3	3	1	2	3	80	undefined	
28	Spain, Zaragoza	3	2	2	2	2	73	undefined	
29	Egypt, Cairo	1	1	1	3	1	47	undefined	
30	Pakistan Nuclear tests	1	1	1	3	1	47	undefined	
31	US, Yucca Mtn, NV	3					20	undefined	

Figure 4: Geographic distribution of all test-sites considered



4.6: Communication and Problem Log

For each test-site, NPA maintained an evolving log or account of communications, whether associated with searches, ground-truth, processing, promotion or other matters. The structure adopted is shown below:

- Site name.
- Communications summary (itemised table of communications).
- Communication details (brief description of each communication, complete originals of which are archived separately by test-site for reference).
- Problems (summary of difficulties encountered).
- Data search.
- Processing.
- General communications.
- Other / miscellaneous

Table 5 summarises the problems encountered with the ERS System in performance of the project.

Table 5: Summary of problems encountered

Problem	Data set/s affected	Effect on project	Status
Slow data delivery	Non-central PAF	Needing to order two data sets for each site (long and short temporal separation) to ensure positive result	ESRIN?
Errors in timing data	Las Vegas, Tucson	Difficulty co-registering data sets Final result of lower quality	PAFs?
FRINGE database not kept up to date	All	Dataset searches not exhaustive	ESRIN?
Missing data in FRINGE database	All	Dataset searches not exhaustive	ESRIN?
Missing lines in data	Kanto Basin	Some parts of the interferogram of lower quality	
Data orders lost while awaiting quota increases	London	Delay	Resolved
Incorrect data supplied	London	Delay	Resolved
InSAR search capability of DESCW faulty	All	Makes searches for B_{perp} and temporal separation compliant data difficult	Ongoing
Lack of data available	Bangkok, Houston, Latrobe Valley, Mexico City	Temporal specifications of data available not-optimal	Mission planning?
Incorrect data entered in to the order system at ERS Order Desk	Davis	Potential for incorrect data supply	Resolved
Data rejected due to a high % of missing data	Houston, Bangkok, Davis, Rotterdam, Ravenna, Latrobe, Lancaster	Replacement data not as temporally suitable as original data. Delays	Resolved

5: ERS SAR DATA ACCESS

For the ERS system to be useful as a tool for commercial subsidence mapping the reliable and prompt delivery of data is essential. Our experiences over the last year highlight some of the problems in data access.

5.1: Slow data delivery

Figures 5 to 7 show the delivery times, by duration, by ground-station, for each dataset. Overall, data delivery times varied widely from 4 to 159 days. The average duration from order to receipt of data was 37 days (more than 7 weeks). This does not however tell the full story, as a *pair* of data is required for interferometric processing. Figure 8 illustrates how long each interferometric pair took to arrive. Here the average wait was 43 days (more than 8 weeks). Data delivery times also varied during the project. As a result of pending deadlines and pressure from ESRIN, data from Prince Albert was being received much quicker near the end of the project than during mid-term (Prince Albert is the ground station principally responsible for most of the SWUS SAR data).

The data delays experienced had a knock-on effect, *e.g.* to the data selection process for each site. The desired temporal parameters of data cannot be specified when subsidence rates are unclear. Ideally, one pair of data would first be ordered and processed. Results of this might then indicate appropriate temporal specifications for another dataset, which in turn would be ordered and processed. Unfortunately the long delivery times experienced made this practical progression unworkable, and the inefficient policy of ordering two pairs of data at the same time became a practical necessity - a 'two shot approach' – one pair with a long temporal separation (*e.g.* 3 years), the other shorter (*e.g.* 1 year) so that one of the two was likely to work.

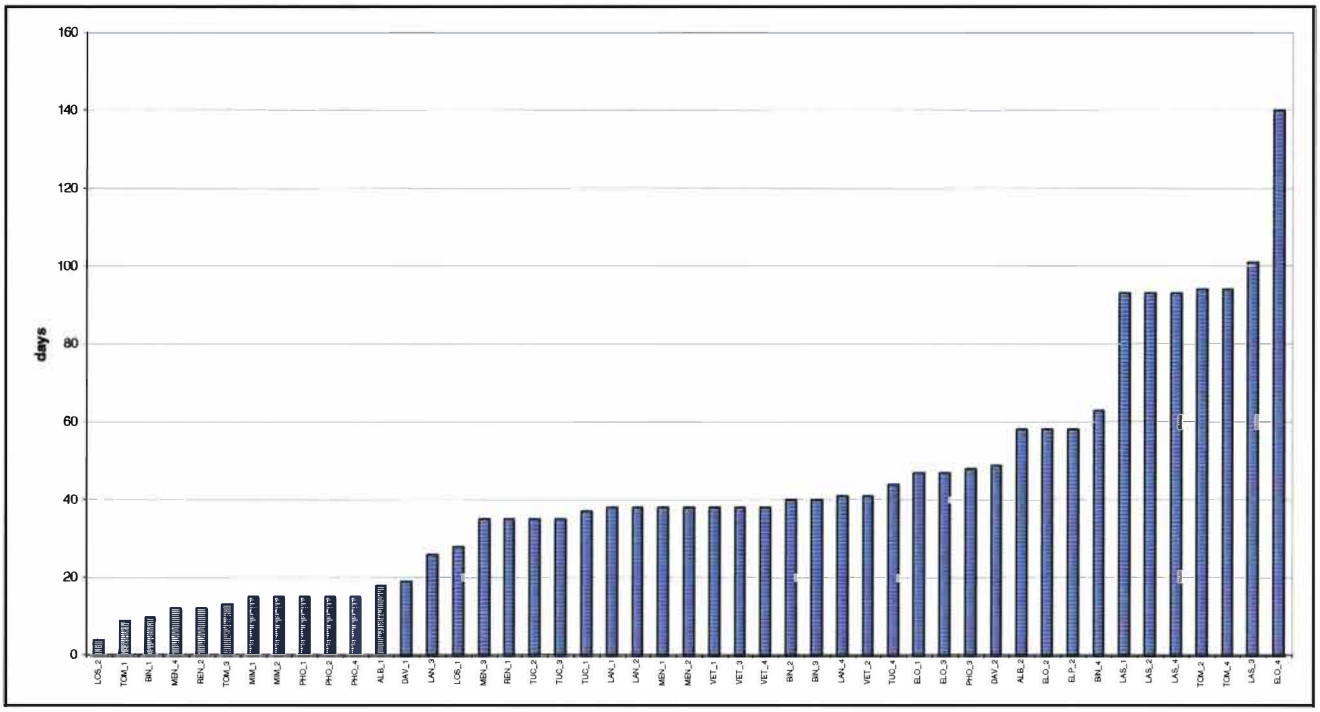
5.2: Reliability of data supply

Data supply was not 100% reliable, as occasionally incorrect frame data was received, for example over London. Also, two data sets ordered from the same orbit over the US were later confirmed by the ground-station to have never actually been acquired, despite both DESCW and the ERS order desk confirming to the contrary. This type of problem along with missing lines in data was aggravated by the slow data delivery cited above.

5.3: Lack of data available

Certain regions of the world have very few data acquired over them. Notable examples from our test-sites are Houston, Bangkok, Jakarta, Latrobe Valley (Australia) and Mexico City (an important region of high seismic risk). Some test sites were rejected due to insufficient data, while inappropriate data sometimes had to be used for other sites as there was no alternative.

Figure 5: Time taken in days from ERS data order to receipt: Prince Albert



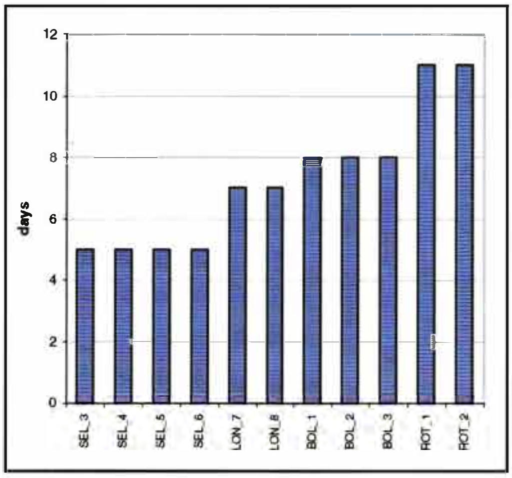


Figure 6: Time taken in days from ERS data order to receipt: Fucino

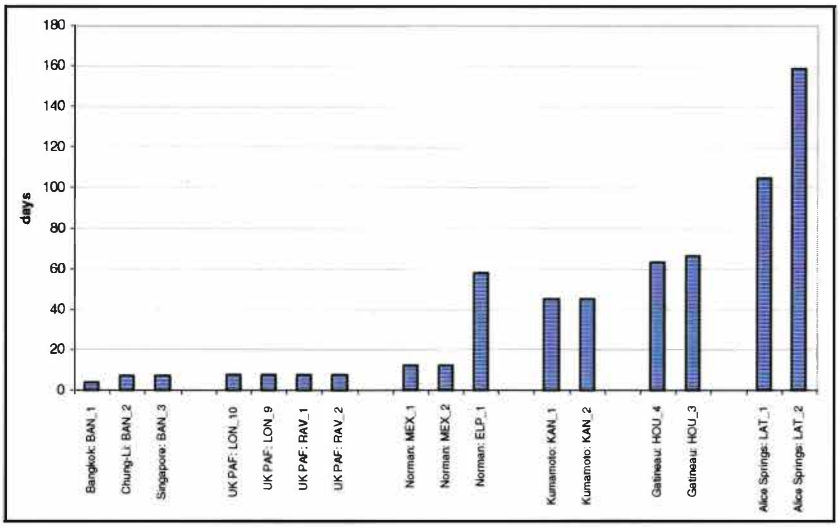
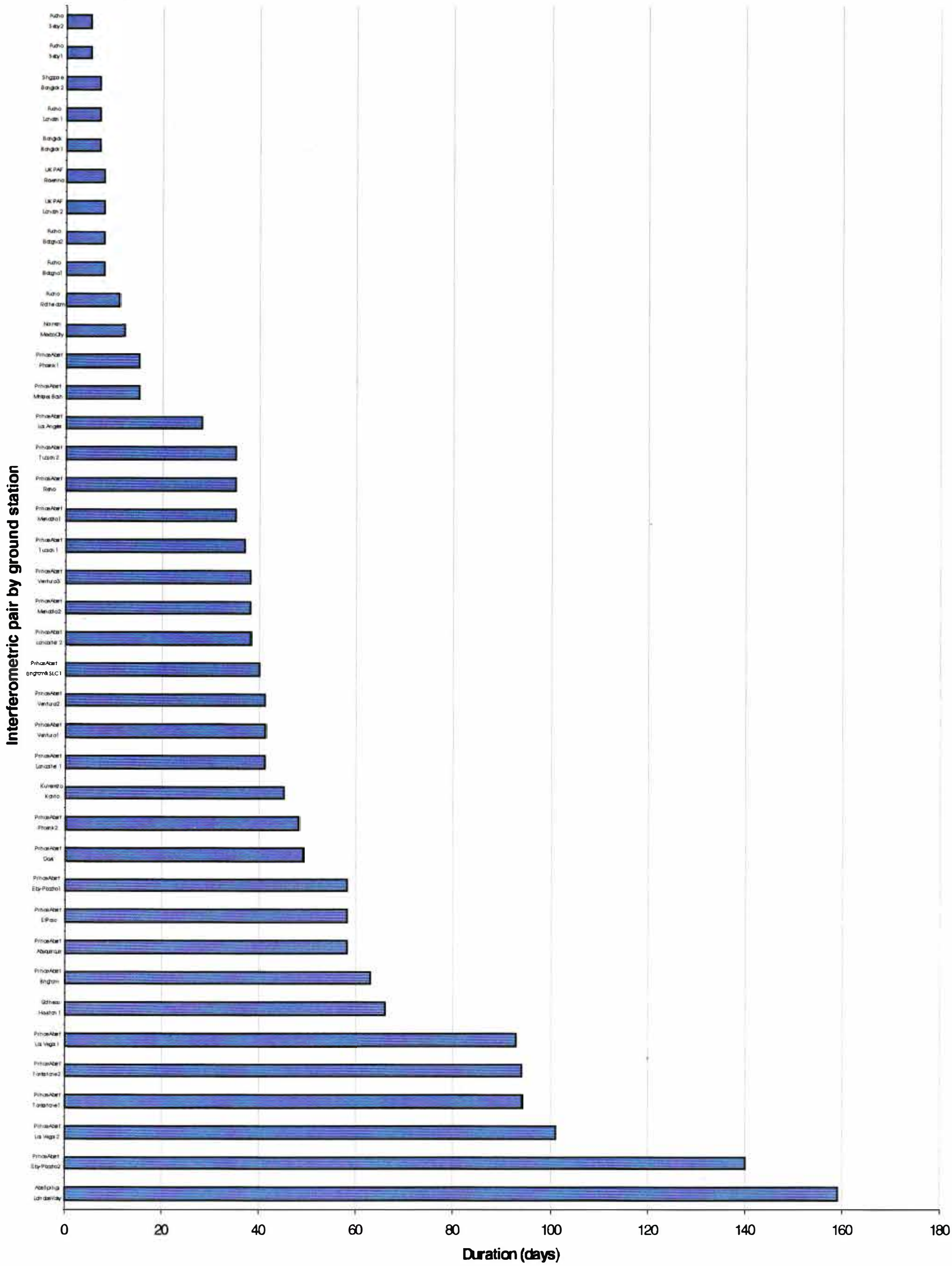


Figure 7: Time taken in days from ERS data order to receipt: Others

Figure 8: ***Time taken in days from ERS data order to receipt of interferometric pair, by ground station***



5.4: DESCW and the FRINGE Database

A number of problems were experienced with DESCW and FRINGE after a move at ESA-ESRIN to incorporate interferometric baseline listings into the new DESCW (Version 4). In addition to the fact that the pair listing within DESCW 4 was not comprehensive, the FRINGE database became either inaccessible or no longer maintained up-to-date.

Previously, using some in-house software to scan the up-to-date FRINGE database, NPA was able to derive the complete, exhaustive permutations of all interferometric pairs for a given track and frame. In contrast DESCW 4 would only provide the interferometric pairs formed from (or relative to) a particular acquisition; furthermore temporal separations associated with each pair were incorrect in DESCW, whereas this critical factor is straightforward to calculate from the FRINGE database using the NPA software.

For these reasons, NPA preferred to continue operating searches using the FRINGE listing. However, with the introduction of DESCW 4, the FRINGE database was not updated for several months, thereby preventing fully exhaustive interferometric pair searches. For some sites with very few available frames this was a particular setback, reducing the number of pair options.

These matters were reported during regular communications with ESA-ESRIN and hence the FRINGE database was eventually restored, initially in a format different to the usual. At the time of writing the FRINGE database is being updated and is in the format expected for pair searches. However, we have noted that FRINGE does not contain within its listing *all* acquired frames, as shown in the DESCW frame listing, and so technically does not provide a fully exhaustive pair listing. We brought this to the attention of ESA-ESRIN four months ago in August 1998, but have not as yet received any indication of a resolution to the problem.

6: INTERFEROMETRIC OUTPUT

6.1: Processing

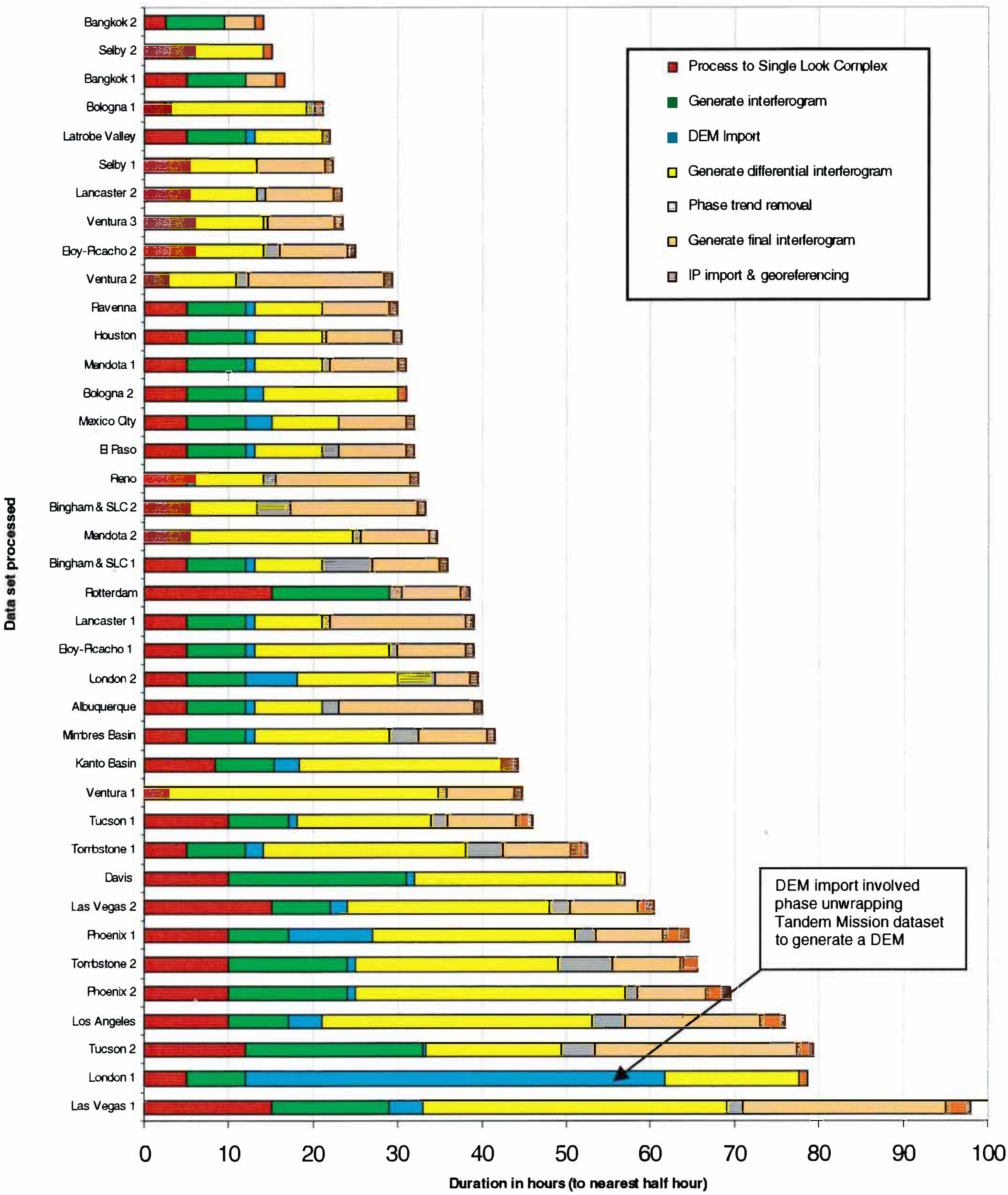
Using NPA's processing chain, there are 7 processing stages in the production of subsidence maps from 'RAW' SAR data. The time taken to perform each process for each dataset was logged (Figure 9). These data illustrate specific processing problems and reveal useful quantitative information on effort required. They also highlight processes which might be targeted for improvements in efficiency. Table 6 lists the 7 processes with their average and standard deviation (SD) times.

Table 6: Average processing times

Process	Average time (SD) (hours)	Total for project (hours/days)
Raw to Single Look Complex (x2)	6.5 (3.4)	255 / 31.9
Generate interferogram	9.0 (4.2)	252 / 31.5
DEM import	3.0 (8.2)	107 / 13.4
Generate differential interferogram	15.4 (8.7)	555 / 69.4
Phase trend removal	2.4 (1.6)	66 / 8.3
Generate final interferogram	10.0 (5.1)	321 / 40.1
IP import, map layout, visualisations	1.4 (0.7)	53 / 6.6
Totals	**47.7 (32)**	**1,609 / 201.1**

Average time to produce subsidence map	**47.7 hours = 6 days** but high SD of 32 hours = 4 days

Figure 9: Production time by process for each interferometric dataset (in hours from 'RAW' data to final map layout)



6.2: Processing difficulties

A number of difficulties were encountered during processing, as a result of problems inherent in some of the RAW SAR or DEM data, for which replacement would either not be a solution or not even an option. We were nevertheless successful in overcoming such obstacles, largely through modifications or enhancements to aspects of the processing chain or of the RAW data itself.

Missing lines

Some of the data had too many missing range lines, causing the RAW-to-SLC processing to halt within the SAR processor. By increasing the usual threshold limit of missing range lines within our software, successful full-scene SLC processing was enabled, with sequences of absent range lines padded out as appropriate with a non-corrupt line.

SWST shifting

Another instance of corruption in RAW data occurred when an erroneous shift of the SWST (sampling window start time) was detected in a range line, causing about a quarter of the scene range lines to be shifted in the range direction in the processed SLC. Once detected, this shift was manually corrected.

Timing errors

There were several instances of errors, of the order of 2 seconds or less in azimuth, in the timing records of RAW data, originating from the Prince Albert receiving station. These azimuth errors had the effect of not only causing location errors in the SLC images of the order of a few kilometres, but also of preventing the successful coregistration of interferometric pairs. Coregistration was only made possible using manually defined ground control points.

DEM import

A variety of DEMs were employed in the difSAR process, but the associated formats did not correspond to our interferometric software's internal DTED format. Consequently, the software was modified to permit the import of all formats of DEM, as well as to convert heights between datums. As a result of these and other changes, the NPA processing system is now more flexible in the range and quality of data that it can accept.

6.3: Quality of results

The volume of interferometric results generated under this programme is extensive, with 39 InSAR datasets processed covering 26 different geographic test-sites. 1 InSAR pair was processed for each of the 13 sites, 2 pairs for 11 sites, and 3 pairs for 2 sites. The categories of results from this comprehensive interferometric catalogue can be broken down as follows: -

Negative result

- Inadequate coherence, *i.e.* no displacements or fringes of any form due to global (full-scene) decorrelation.
- No discernible displacement fringes due to phase invariance.
- No discernible displacement fringes that correspond to known ground-truth, *i.e.* beyond spatial resolution.

Positive result

(Grades of identified surface movement are listed in section 6.4: *Interpretation of results*)

Figures on the breakdown of results for the 26 sites according to the above categories are given in section 8: *Markets Engaged.*

Examples of negative results include Rotterdam (the Netherlands) and Tombstone (Arizona) which suffered respectively from complete decorrelation and the lack of (known) displacement fringes in the coherent result. Whilst one would expect the urban region of Rotterdam to have presented a sizeable, coherent zone, even across a long temporal separation, the result is disappointing. The cause of this decorrelation may be attributed to the surrounding agricultural area, or to snowfall and/or precipitation events on one or both scenes. Conversely for Tombstone, the coherence is adequate, but the known ground displacement over this small town appears to have been beyond the resolution limits of the system.

A large number of positive results, concentrated in the US, were prone to atmospheric phase artefacts spread across the full-scene interferograms. However in all cases this did not ultimately prevent identification and analysis of displacement fringes, though the chief recommendation in the interpretations is to repeat processing with an alternative pair where atmospheric factors are diminished or absent (as in the case of most night-time acquisitions). The mechanisms and typical magnitudes of atmospheric artefacts are described in section 6.4: *Interpretation of results.*

DEMs employed in the differential process ranged from 1km to 50m grids, e.g. GTOPO-30 and NPA's (UK) EuroDEM respectively. In some cases (particularly where only a coarse or no DEM was available) the interferograms were generated non-differentially under certain conditions. Such conditions occurred when the altitude of ambiguity of the pair was sufficiently high, *e.g.* > 1000m, or where the topographic variation was minimal *e.g.* Bangkok (where in fact the available, 1km DEM showed zero relief change).

The vertical accuracy of the various DEMs ranged from the order of 2m to some 20m. On the whole we were satisfied with the DEM registration and elimination of the topographic phase. This is aside from a limited number of cases where some topographic fringes persist, but their nature is clear to the interpreter, from an examination of the corresponding regions in the DEM or amplitude imagery.

6.4: Interpretation of results

An initial interpretation was made of all interferometric output (interpretations are provided with each test-site output in the Appendix). Below is a discussion of the issues involved in interpretation.

Background

Differential interferograms demonstrate phase changes between two successive radar images separated by a period of time, typically a few years in this work. Apart from possible surface movement, phase variations can arise from a number of other causes, namely:

- Uncompensated topographic features
- Platform position estimation errors
- Atmospheric perturbations

The likely magnitude and characteristics of these need to be borne in mind when screening the interferometric data to identify probable sites of surface movement. Some brief observations are made below.

Uncompensated topography

A differential interferogram is by definition processed in conjunction with a digital elevation model (DEM), such that the effects of topography are subtracted from the output phase image. The magnitude of topographically related phase errors is thus a function of the quality of the DEM, the accuracy with which it is co-registered to the dataset, and the separation between the satellite orbits

(Bperp). Each differential interferogram presented is annotated with the 'altitude of ambiguity' parameter for the dataset; this number corresponds to the uncompensated topography necessary to cause a fringe cycle in the interferogram (fringe interval). With DEM errors typically <<20m, and with altitudes of ambiguity typically >300m, the maximum topographically related phase error corresponds to at most a small fraction (<10%) of a phase cycle.

Platform position errors
The interferograms have all been generated using the best available data for the satellite orbits, nominally accurate to a few wavelengths. However, uncompensated positioning errors can occur, varying slowly on a scale of a few wavelengths over a 100km scene. These positioning errors are compounded with subtle changes in the average refraction characteristics of the atmosphere, which in effect move the apparent location of the orbit track. The overall effects are observed as slowly varying (and usually linear) large scale phase trends across the interferograms. The interferograms presented here have, where it seemed appropriate, been corrected for linear phase trends to ease interpretation.

Atmospheric perturbations
The characteristics of the atmosphere are not invariant; apart from gross changes between data acquisitions, subtle variations can occur on a smaller geographic scale of order 5-20km. The effect of these variations can be to alter signal path lengths by refraction and cause small localised phase variations in the interferograms of possibly up to half a fringe cycle. Such effects can only be wholly eliminated by undertaking a series of interferometric analyses of a given location with different datasets. However, in general the spatial characteristics of atmospherically-related effects are qualitatively very different from those associated with ground subsidence. It is important to recognise that while in principle differential interferometric analysis is sensitive to millimetric scale movements, on any one pair of interferograms the accuracy is limited by atmospheric effects in the order of half a phase cycle, or 1cm.

Classification
To help structure interpretation of the results shown in the Appendix, a 4-point classification scale was devised for categorising identified features of interest, as follows:

Category A: Unambiguous surface movement on a large geographical scale, or of a large magnitude.
Category B: Unambiguous surface movement on a small scale or magnitude.
Category C: Probable surface movement.
Category D: Feature of possible interest or significance.

It is important to note not only the possible causes for interferometric features discussed in the interpretations, but also the modulo nature of the phase images - an abrupt change from white to black (or vice versa) is of no great significance in view of inherent small scale variations in phase - rather, it is the spatial characteristics, or abrupt changes in phase gradient which are of interest.

7: PRODUCTISATION

An important aspect of the interferometric processing system is the conversion of the raw fringe displacement results into meaningful, graphic products. This process includes (but is not limited to) the enhancement of the raw interferometric results and merges with ancillary data to convey the derived displacement information within geographic, geological, or other contexts, that will be clear to users of this information. During the project NPA has experimented with different enhancement and visualisation methods. Some of these are described below, though it should be noted that this process is continuous and ongoing. Whilst these methods are distinct and separate, visualisations in practice will incorporate combinations of several, if not all.

7.1: General methods

Fringe extraction with backdrop
The displacement fringes can be digitally cropped out, *e.g.* when they occupy a small region or where their impact is lost because of phase artefacts in the full-scene differential interferogram. This extract can then be overlaid, either as greyscale or with a colour map applied, onto *e.g.* colour optical or greyscale radar amplitude images, map layers, or a combination.

Vector overlays
Roads, railways, rivers, lakes, coastline and other vector data can be overlaid onto the interferogram to add contextual information, either as additional layers in a visualisation or, where no other layers are available, onto both the raw interferogram and *e.g.* the amplitude image for cross-referencing features in the two layers.

SAR/InSAR/DEM colour composites
Assigning a combination of the elevation, coherence, phase, amplitude (or mean, or difference) images to the red, green and blue layers creates colour composites. Preliminary results indicate that with the non-tandem results used in this project the quality of the composite is reduced when the noisy, low-value coherence map is used as one of the layers.

Coherence-masking
One solution to the above coherence-related problem is to mask composites (or single layers, such as the phase image) with a coherence layer thresholded at a relatively high value, *e.g.* 40%. However, again because of the non-tandem nature of the results, thresholded regions are not always clearly defined or contiguous, and high coherence pixels can also appear within low coherence regions, giving a speckly, frittered effect, though these can be reduced with appropriate filtering.

Stacking
When two differential interferograms are generated from two separate and distinct temporal epochs, the total amount of fringe displacement, between the earliest and most recent SLC dates (less the period between epochs), can be estimated by effectively summing the phases of both interferograms into a single 'stacked' interferogram. This layer will exhibit more displacement fringes than the two, separate interferograms; it is useful for reinforcing or amplifying displacement fringes, and the method can be applied to a multiple time series of interferograms.

3D perspective views
This is a common method to emphasise local relief and give perspective to the results, by draping the two-dimensional layers onto a 3D surface formed by the associated digital elevation data.

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7.2: Phase unwrapping

Unwrapping the fringes of a differential interferogram gives a continuous height displacement model, which can be incorporated with the original elevation data (though magnitudes will differ in general) or can be used as a 3D elevation change map in its own right. In practice, however, phase unwrapping is applied to very high coherence tandem interferograms; with subsidence interferograms corresponding to small displacements over several years, phase unwrapping is not effective, or even possible, due to the low coherence levels. An alternative to phase unwrapping for these data is manual digitisation or contouring of constant phase values, *e.g.* at successive fringe cycle boundaries.

NPA is nevertheless undertaking a performance comparison test of several phase unwrappers, which originate from ESA, JPL and the DeRAIn software. Figures 10 and 11 show the full-scene ERS amplitude image and tandem interferogram of a mountainous area in Turkey (encompassing the region of the 1995 Dinar earthquake). Figures 12, 13 and 14 that follow are the unwrapped phase results generated by the three different systems. A preliminary, visual analysis of the results shows the ESA software as achieving the best phase unwrapping performance.

***Figure 10*: Full-scene ERS amplitude image over the Dinar, Turkey region**

Figure 11: Wrapped phase interferogram from tandem SLC pair

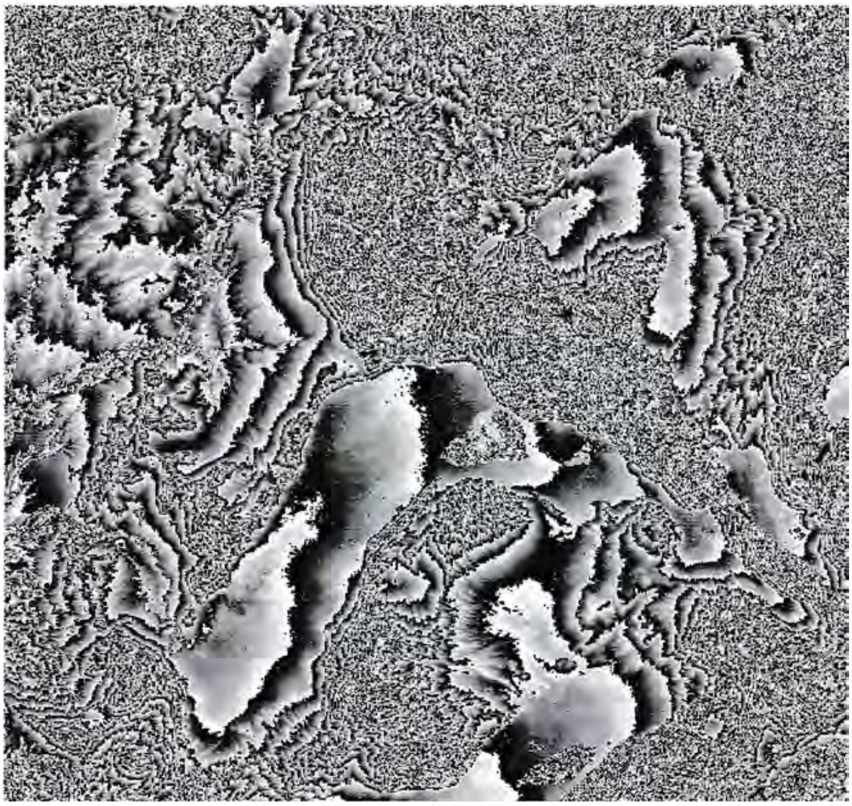


Figure 12: Unwrapped phases using the ESA software

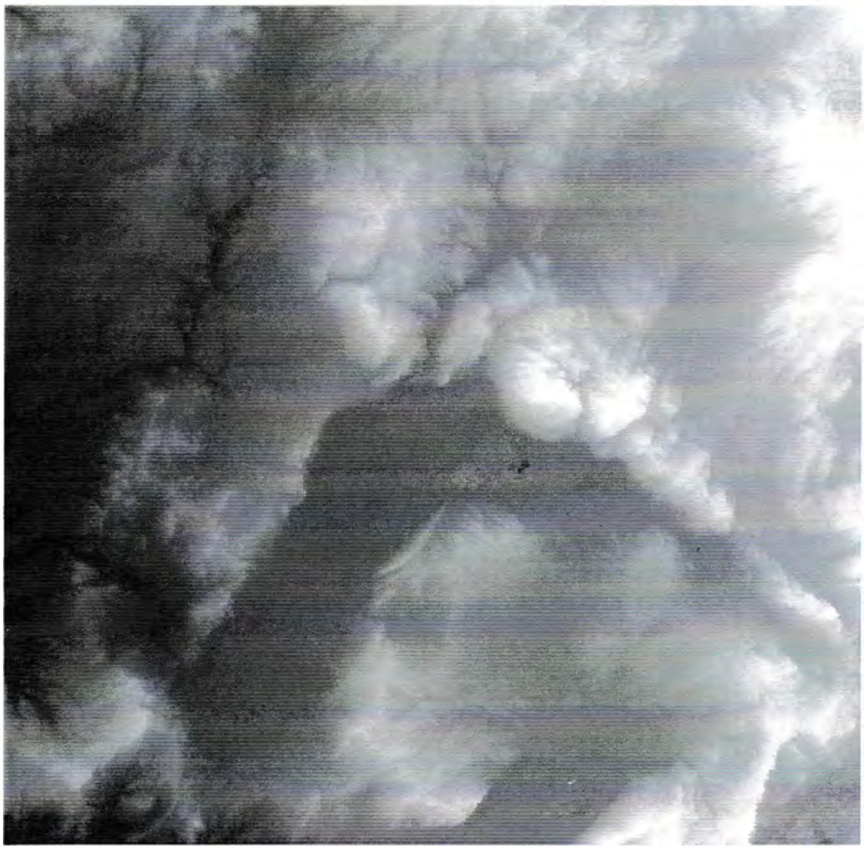


Figure 13: Unwrapped phases using the JPL software

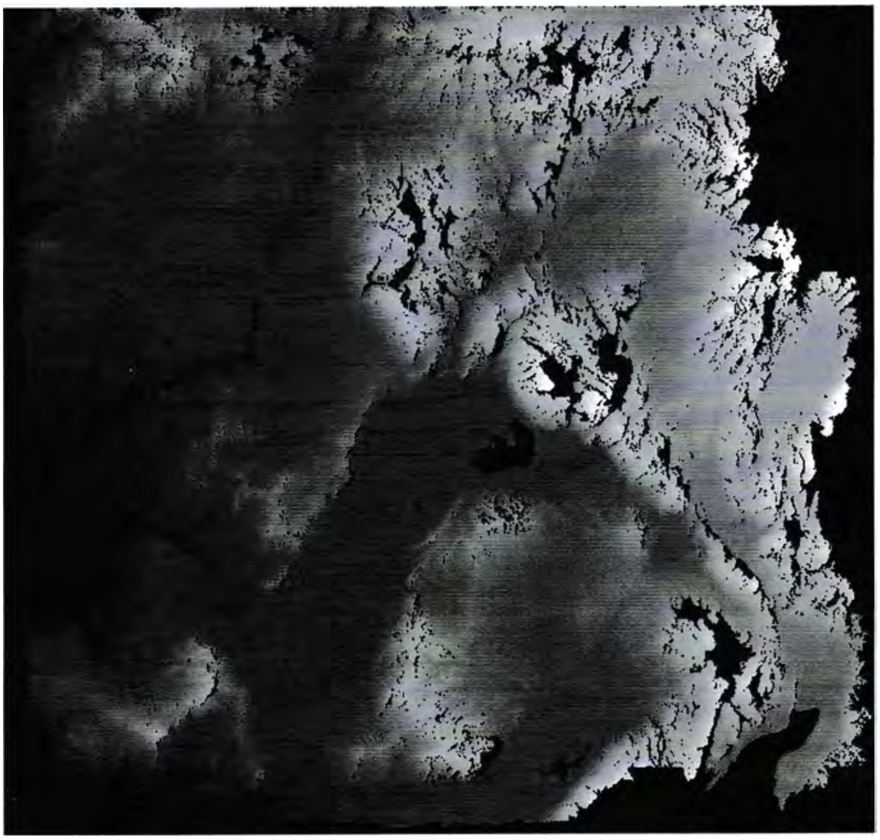
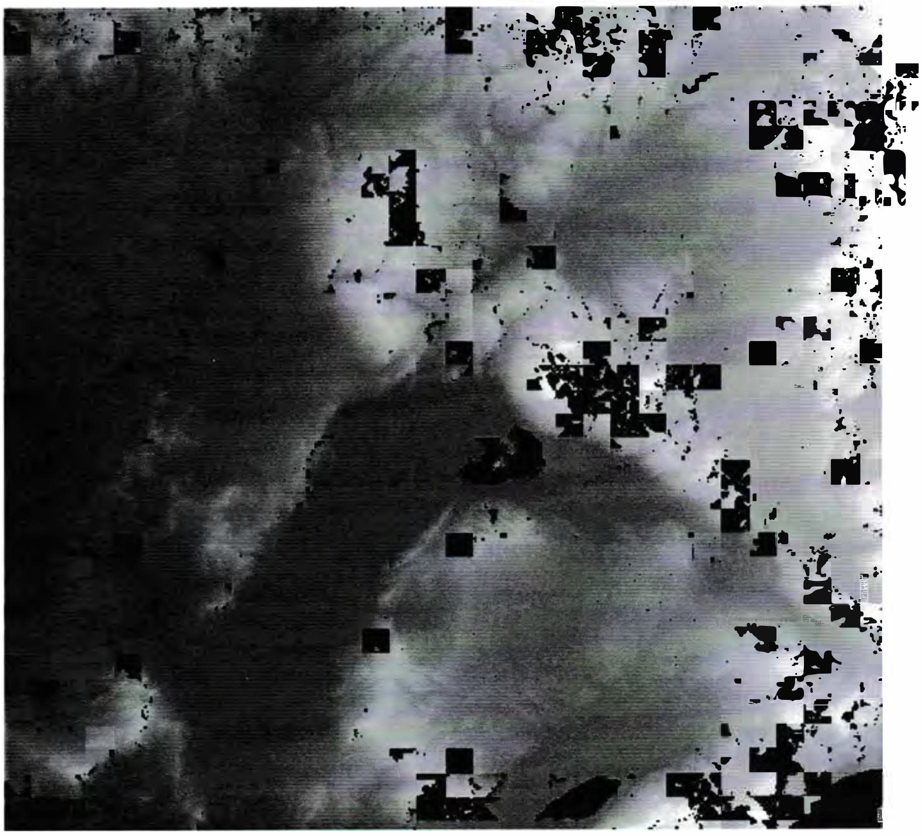


Figure 14: Unwrapped phases using the DeRAIn software



8: MARKETS ENGAGED

Market were engaged largely through the establishment of contacts for ground-truth as parties interested in subsidence tend to either already possess, or can source quantitative information. The most appropriate contacts were not always established. In many cases, only academics could be found, particularly in poorer countries where knowledge about subsidence tends to be limited to their domain only. In such cases, these sites were still sometimes pursued and processed as their potential marketability appeared promising, the academic information allowed data specification and ordering, and it was anticipated that a commercial contact would still be identified during the project term.

Established contacts could only be pursued further if results of the InSAR processing for the site were positive. Not all results were positive as shown in Table 7:

Table 7: Processing success

test-site category	**sites with positive results**	**sites with negative results**	**total sites**
SWUS (plus Houston and Mexico City)	13 (72%)	5 (28%)	18
Non-US sites	5 (63%)	3 (37%)	8
total	**18 (69%)**	**8 (31%)**	**26**

Reasons for negative results included:

- inadequate coherence
- ambiguity presumed to be caused by varying degrees of atmospheric disturbance
- no displacement detected
- known displacement apparently beyond spatial resolution
- SAR data in archive temporally inappropriate

8.1: Markets engaged in the US

8.1.1: Arizona Department of Water Resources

Many towns and regions in the State of Arizona are suffering severely from subsidence caused by overdrafting of groundwater. The Arizona Department of Water Resources (ADWR) has a responsibility to monitor such subsidence and makes extended efforts with a number of monitoring campaigns in operation using conventional survey tools. An example of this is the array of six extensometers around Tucson, costing half a million dollars in hardware alone. NPA's meeting with the ADWR in April 1998 (see section 9.2) generated much interest and certain staff have become advocates of the technique. These contacts have been strongly supported by NPA in terms of hard and softcopy output, slide-sets and other promotional material for presentations that have been made at various local symposia. Most recently, the ADWR has gained an interest from Tucson City Hall and Tucson Water who have since requested copies of specific results, NPA remains optimistic that a commercial contract will be forthcoming, especially in the light of additional promotional activity planned.

8.1.2: Arizona Sonora Desert Museum

The promotional activity of the ADWR exposed NPA's work over Tucson to the Sonora Desert Museum. They have since contracted from NPA a poster for a 2-year educational display as part of their overall exhibit on the region's water resources and problems.

8.1.3: US Geological Survey

Though never anticipated as a commercial customer, the US Geological Survey Water Resource Department (USGS WRD) has proved a valuable contact. The local branch of the USGS WRD, based in the University of Arizona in Tucson, works closely with the ADWR, and in fact arranged the original contact between them and NPA. They remain a strong and supportive advocate and do what they can to promote NPA's work (*e.g.* the project's results for Tucson are being featured in an official circular newsletter of the USGS WRD). Other contacts within the USGS have been established and remain useful sources of information and gateways for the careful dissemination of the project's results.

There are some skilled practitioners of ERS InSAR within the USGS and some close connections between them and workers at JPL. Their work, however, appears more academic and piecemeal in nature and not perceived as any threat to NPA's commercial aims. As a government organisation, the USGS is not geared-up to provide any sort of operational service and there seems more likelihood of NPA selling subsidence map products to USGS than the USGS making products available to order for, say, the ADWR.

8.1.4: Harris-Galveston Coastal Subsidence District

The search for ground-truth concerning the well-known subsidence of Houston quickly identified the *Harris-Galveston Coastal Subsidence District* organisation (HGCSD). Fluid abstraction in the region has caused large-scale subsidence and resulted in periodic inundation and widespread flooding. The problem is serious enough that the Federal Emergency Management Agency appointed a special unit to prevent, monitor and remediate against the causes and effects of subsidence. The results of NPA's data processing over this site, though not particularly clean, were in complete accordance with known ground-truth, clearly demonstrating the remarkable value of ERS InSAR. The HGCSD were sufficiently convinced to have since commercially contracted NPA for the processing of another dataset: the project's first full commercial sale! This contract was won because the customer had a genuine requirement that ERS InSAR could satisfy, and, importantly, because they were informed about ERS InSAR (they had in fact already been approached by a team from the University of Texas who had quoted to perform similar work, but NPA was perceived as more likely to deliver).

NPA believes in the potential of using radar corner reflector arrays to conduct regular large-scale point-sample surveys of ground displacement (*NPA's SNAP Project, CEO SCA, 1998*). One of the aims to the work contracted by the HGCSD is to identify possible locations for the reflectors of such an array, which could then be monitored on a regular basis, say, four times a year. If this concept proceeds, a significant contract could ensue involving the supply of corner reflectors and the ongoing processing of perhaps up to 20 ERS scenes per year.

8.1.5: Bureau of Land Management, Utah

Attempts were made to interest the State Bureau of Land Management for Utah because of anticipated results over Salt Lake City and the some surrounding areas. Little progress has been made here, except that NPA possesses a contact database for the organisation, and the results generated were positive showing a number of subsidence sites (see Appendix). Contact will be pursued as part of forthcoming promotional activity.

8.1.6: Kenecott Mining Inc, Utah

The Bingham Copper Mine in Utah, worked by Kenecott Mining Inc., is the largest man-made ground excavation in the ground in the world. As it was included within the same footprint as other known subsidence sites in the region, the mine was considered of interest to see if InSAR could provide any information on extraction rates by revealing any evolving decorrelation. There was also interest in attempting to map any micro-seismic activity typically associated with such excavations. Our contact with the Environmental Section of the company was initially enthusiastic and promised comprehensive ground-truth including a series of high-resolution DEMs corresponding to the developing topography. The initial enthusiasm however turned into a reluctance to communicate as though the company had decided it was not in their interest to participate with an unknown group who might determine information on their commercial output. Paradoxically, processing results were negative, due largely to inadequate spatial resolution and shadowing of the steep, near-range sides of the mine.

8.2: Main non-US market sectors engaged

8.2.1: Risk Management Solutions Ltd. (formerly *CARtograph Ltd.*), UK

The *Project strategy and quality analysis plan* placed most emphasis on addressing risk management consultancies in relation to the UK insurance industry. This was because the UK insurance industry has in recent times lost substantial sums against unanticipated claims for subsidence damage and they have no practical or reliable way of assessing their liability except by analysing claims history. The industry is interested in subsidence information, particularly that related to clay shrink-swell, accounting for 70% of claims. As London and other built environments in the UK suffer from this problem, the application of ERS InSAR appeared promising.

The London results were however disappointing revealing no unambiguous evidence of large-scale subsidence or its coincidence with known areas. The conclusion drawn was that the localised effects of parts of buildings subsiding under their own weight were sub-pixel with no continuity in displacement to the next affected building. The effects were outside the spatial resolution for ERS InSAR which, when applied to datasets with significant temporal separations, only gives at best pixel sizes of ~50m, but more usually 100m.

In efforts to improve resolution, a second differential interferogram was generated using a phase-unwrapped Tandem Mission interferogram instead of the 50m DEM first used. However, this made no useful difference.

8.2.2: Japanese Geological Survey

The positive results for the Kanto Basin (Tokyo) test-site, were disseminated in both hard and softcopy to a number of organisations in Japan. Though the free dissemination in Japan might be a risk, this market is notoriously difficult to penetrate and the sharing of results seemed the only option. Results were sent to RESTEC, The Japanese Geoscience Institute (Japex) and the Japanese Geological Survey. The latter has shown interest to which NPA has responded by supporting them with presentational materials. A presentation was made and a poster displayed at a recent conference in Tokyo in December 1998 which generated some interest. Since then (and at the time of writing), the Japanese Geological Survey has emailed saying they have four further ERS SAR scenes of their own of the Tokyo area, and request NPA to confirm previous quotations made to them for the cost of InSAR processing. They went on to say they are interested in applying ERS InSAR to other areas as well.

8.2.3: Esteyco (civil engineers), Madrid

Test-site searching revealed a subsidence problem in the Zaragoza region of NE Spain. Promising interest has been gained from *Esteyco*, a Spanish company of consulting engineers, responsible for part of a high-speed rail link through the region. Comprehensive ground-truth has been supplied enabling the identification of data. We await further communication before proceeding.

8.2.4: Asian Institute of Technology (Rob Schuman)

Ground-truth for known subsidence due to the steady sinking of Bangkok, was supplied by AIT, but again problems of poor data availability and inadequate coherence prevailed, and results were negative.

8.3: Conclusions on market sectors engaged

The failure of NPA to win InSAR work from most of these markets during the project term should not be taken as meaning that a market does not exist. On the contrary, most markets have been extremely interested in the capabilities demonstrated by ERS InSAR, though sometimes a little incredulous at the outset. As more examples are generated which are in accord with known ground-truth and show reliability, credibility is growing.

The potential of InSAR combined with radar corner reflector arrays offers a possible solution to some of the applications commonly defeated by inadequate coherence, and might allow a steady acquisition of point sample data over large areas at a time. NPA's CEO SNAP project (01.11.98 – 31.10.00) will serve to prove the operational potential of such a system

NPA is optimistic that significant markets will develop over time. In the SWUS for example, the ball is now rolling with a wider-spread of interest developing. Risk managers in the region will soon have to justify why they are not using ERS InSAR as it so obviously provides the information they need, and at a fraction of the cost. A number of other teams have now realised the potential of ERS InSAR to map subsidence in their areas and are processing data. NPA considers this positive and to their advantage as the work is developing the overall portfolio for ERS InSAR, improving exposure and credibility, but is not, on the other hand, threatening any competition. Most of the work is academic and piecemeal in nature, and few of these organisations, if any, could offer any kind of operational service to which a third party could go to contract work.

9: PROMOTIONAL ACTIVITY

A number of targeted and direct promotional activities were undertaken during the course of the project detailed in the following sections. Note that promotional activity was not included within the budget for the project and was financed by NPA directly.

9.1: Sharing results

With such radical technology, 'taster' products are needed. Risk managers have to *use* the information derived from ERS InSAR to be convinced before any consideration of purchase. There was some commercial risk attached to the 'free' dissemination of output, but this was balanced against the need to stimulate an ongoing interest and attract active participation in ground-truthing. Results were also historic, as no new ERS SAR data was acquired for the project, so contemporary measurements were still outstanding.

9.2: US visits

In April 1998, NPA held two small seminars in Tucson, Arizona. The first was held at the offices of the US Geological Survey in the University of Arizona and was attended by representatives of the US Geological Survey and hydrologists from the Arizona Department for Water Resources (ADWR). The second seminar was held at the company offices of Dames Moore Consulting Engineers, and was attended by hydrologists from that company and other members of ADWR. A portfolio of various InSAR results from NPA's BNSC ADP project *CivInSAR* was presented together with the new results just generated for Tucson for this project. To most attendees, this was their first exposure to ERS InSAR and there was some mystification as to the technique. However, though caution was expressed the Tucson results were received with enthusiasm and intrigue. Since then, digital, georeferenced versions of the results have been passed over to the contacts to maintain interest and stimulate usage. This has led to a continuing relationship, particularly with the ADWR whose support is proving a valuable asset.

In September a further visit was made to the USA to the contacts established for the Harris-Galveston Coastal Subsidence District, Houston. This organisation found the results, which were in fact rather poor and noisy, so compelling and in direct agreement with their known ground-truth, that in November they placed a full commercial contract for NPA to process a further dataset with a longer temporal separation. One of the aims to processing these data is to identify possible sites for the installation of permanent radar corner reflectors for a long-term InSAR monitoring campaign.

9.3: Lecture support

Our contacts at the ADWR presented some of the project's results at the *Annual Symposium of the Arizona Hydrological Society.* In support of this event, NPA produced a 35mm slide-set of the graphics for better presentation, plus various NPA publicity for distribution. In the short-term, this event has led to 9.4.

9.4: Museum exhibit

Staff from the Arizona-Sonora Desert Museum attended the *Annual Symposium of the Arizona Hydrological Society* and have since placed a commercial order with NPA for a poster of the Tucson InSAR results to be used as part of a 2-year educational exhibit on the region's water resources.

9.5: Mailshot

Two mailshots were conducted. The first to a list of those attending the *Fifth International Symposium on Land Subsidence, The Hague, 1995*. Faxes and emails were sent to contacts in 26 of the most relevant organisations world-wide. Responses for 9 test-sites were received. 3 of these, Zaragoza (Spain), Ravenna (Italy) and Rotterdam were seriously considered, with the last 2 being processed. Both results were negative.

NPA was aware of the bias towards the SWUS and so during the last third of the project tried to broaden the global distribution of the project's test-sites. Addresses from the *Directory of Geoscience, GeoTimes* (October 1996) were used to send 73 messages to various contacts. Most contact names were unknown, and so messages were addressed for the attention of the following:

Senior Hydrologist
Senior Geotechnical or Civil Engineer
Senior Mining Engineer
Senior Environmental Geologist
Senior Remote Sensing Geologist

Only 3 responses were received none of which were serious contenders for inclusion in the work. The conclusion was that the mailshot was too indirect, obscure and cold.

9.6: Presentations

A number of presentations have been made to various audiences involving the project and its output (date order).

- **Japex Geoscience Institute Inc.,** January 98: Presentation made at NPA offices to Mr. Takashi Nishidai on general NPA InSAR capabilities
- **Knight Piesold Consulting Ltd.** (civil engineers), **UK**, March 98: Slide presentation made in Kent to 15 members of staff interested in the practical uses of EO data.
- **Arizona Department of Water Resources**, USA, April 1998: (as described in section 9.2)
- **US Geological Survey Water Resources Department**, USA, April 1998 (as described in section 9.2)
- **Dames Moore** (consulting engineers), USA, April 1998 (as described in section 9.2)
- **Risk Management Solutions Inc**., CA, April 98: Presentation made in California to the principle EO specialists of the world's largest commercial risk management consultancy.
- **RESTEC,** June 98: Presentation of NPA InSAR capability made at DERA Farnborough.

- **Institute of Electrical Engineers, UK:** *Seminar on SAR applications*, July 98: Paper presented in London with Andy Smith of Phoenix Systems - *Towards the operational application of ERS SAR interferometry*.
- **WS Atkins Consulting Ltd**. (civil engineers), UK, July 1988: Presentation made at NPA to members of their Geotechnics and Foundation Division.
- **Western European Union Satellite Centre**, Madrid, September 1988: Presentation made to five WEU image interpreters at a commissioned meeting at the Farnborough Airshow, UK.
- **Symonds Travers Morgan Ltd**., (civil engineers), UK, October 1988: Presentation made at NPA offices to the company's senior geophysicists and engineers responsible for EO data usage.
- **Eurisy Colloquium**, *Space Techniques for Environmental Management in the Mediterranean*, Athens, October 1998: Slide presentation made - *Towards the operational application of ERS SAR interferometry.*
- **University College London,** November 1998: Presentation made in the Department of Geomatic Engineering to current MSc Remote Sensing student intake.

9.7: Surveying World

The UK journal *Surveying World* will be placing a two page colour article, written by NPA, in their March 1999 edition. Using examples from this project and others, the article will focus on ERS InSAR as a surveying tool.

9.8: CEO contract

NPA has won a fully-funded 6 month contract under the CEO's *EO Product Development and Marketing* initiative, entitled *CivInSAR Subsidence Mapping* (CSM). The aim of CSM is to 'package' the results of this ESA project and make a further visit to potential customers in the US. Packaging will involve the translation of 'raw' interferograms into products of intuitive meaning to subsidence risk managers, *e.g.* coinciding results with groundwater reservoir locations and extent, fluid abstraction points, geology, demographics and infrastructure, production of cross-sections and 3D visualisations.

The comprehensive distribution of positive US results generated from this ESA-funded project now makes a convincing and unique story, difficult to ignore by those responsible for subsidence mapping. It is hoped this further promotional activity will provide the final kick-start required to establish viable sales in the US (not forgetting the existing Houston success!).

10: COMMERCIAL POTENTIAL

10.1: Successes

Identifying an operational application

The over-riding success of the project is the demonstration by NPA of an operational application of ERS InSAR. It can be stated that in the application to subsidence caused by fluid abstraction in the SWUS and Houston, the combination of ERS system design and the SAR data archive enables generation of subsidence map products that closely match the requirements of risk managers on the ground.

The SWUS on its own offers a large market worth perhaps a maximum of a quarter of a million USD per footprint per year (processing 20 datasets per year at 10,000 USD per dataset plus data, and presuming maximum take-up and the continuous supply of appropriate SAR data). NPA has so far demonstrated useful subsidence information from 13 footprints.

Gaining a strong network of contacts

Searching for test-sites established a wide and varied network of contacts in many fields, representing an ongoing and valuable information resource. If not before, these contacts are now at least all aware of ESA, NPA and ERS InSAR.

The early outstanding results for Tucson proved invaluable in attracting a friendly, helpful and enthusiastic set of advocates, representative of real markets. Subsequent work sent to these contacts has served to widen the network and strengthen ties further. It has also shown these important contacts that the technique is *reliable*. Ongoing support from the ADWR and USGS WRD has resulted in various local publicity and sales leads.

Making sales of ERS InSAR subsidence map products

By placing a contract with NPA for further work, the HGCSD (Houston) have indicated their acceptance of ERS InSAR as a viable and economic tool for the provision of subsidence maps. At the time of writing, the data for this contract have not as yet been received (quoted 4-6 weeks). We do however anticipate positive results and look forward to the possibility of a longer-term InSAR monitoring campaign over the region. This sale also provides NPA and the technique with the beginning of a credible portfolio of actual sales, useful in persuading other potential clients.

Demonstrating that the ERS SAR data archive is adequate

The project has shown that the coverage and frequency of acquisitions made by ERS-1/2 has been largely adequate to fulfil the criteria for application to SWUS subsidence. The FRINGE database has also been shown to contain a largely adequate population of appropriate Bperp-compliant datasets spanning useful epochs for most regions of interest. There have been exceptions.

Optimising the processing chain

The project has enabled NPA to further refine their routine production of interferometric products. A number of additions and modifications have been made to the processing chain as a result of the project (*e.g.* DEM import routines, 'RAW' data batch processing, phase unwrapping options, etc). The analysis of processing shown in section 6 is extremely useful in quantifying the distribution of costs involved in interferometry. It also helps identify processes that might be optimised to increase throughput.

10.2: Obstacles

10.2.1: Obstacles in the system

Coherence

Inadequate image coherence is *the* fundamental constraint to differential SAR interferometry. Notwithstanding the factors mentioned above, there are physical constraints inherent in the process that will always prevent some subsidence from being monitored in this way (*e.g.* displacements under dense vegetation, slow displacements under annually flooding salt flats, displacements under moving sand-sheets). These constraints may be somewhat alleviated, however, by the use of radar corner reflectors.

Spatial resolution

Subsidence applications involve significant, coherence-reducing, temporal separations between data acquisitions, and even with the semi-desert landcover of the SWUS, the average working pixel size in an interferogram is around 100m. This is adequate for the types of contiguous subsidence caused by fluid abstraction in the SWUS, or say by earthquakes. But for some potentially lucrative applications, this resolution is far too coarse (*e.g.* clay shrink-swell effects in London).

Temporal resolution

ERS can make a repeat acquisition every 35 days. This frequency might be too high if orbit control was perfect for the rates of displacement occurring in the SWUS and Texas test-sites, which the results show range between 1 and 3 cm/year. Four times a year might be adequate. However, ERS is not always tasked to make repeat acquisitions and orbit drift limits the number of Bperp compliant datasets.

Displacement resolution

In practice, ERS InSAR has a displacement resolution determined by one complete phase cycle – 2.8cm in line-of-sight range, or approximately 3cm vertically. The 1-3cm/year displacement in the US can be detected because the arid landscape provides sufficient coherence to allow the generation of interferograms from multi-year separations. A SAR operating at shorter wavelengths might have detected more subtle, slower displacements, but on the other hand, would be even more sensitive to vegetation than ERS. A SAR operating at longer wavelengths might have had more success at generating positive results over the more temperate conditions of Europe, but require faster rates of displacement. NPA does not have the experience to suggest whether the 5.6cm wavelength of ERS is best for subsidence mapping, but suspects that a range of alternatives would be optimum to cater for the diverse range of displacement rates, extents and landcover associated with subsidence the world over.

Atmospheric perturbation

As mentioned in section 6.2.2, atmospheric refraction can cause ambiguity in interferograms. Simultaneous, high resolution meteorology would be useful in order to eliminate potential artefact-prone pairs, but is not operationally available.

10.2.2: Obstacles in the process

SAR data access
NPA believes there should be a 2-4 week turn-around from order to despatch of an ERS InSAR product. In some cases, NPA was quoted up to 12 weeks with actual receipt taking 4 months. To be commercial, NPA needs to be in receipt of data from Eurimage within 14 days of order maximum (see section 5 on data access). Better systems of quality control are necessary before data is despatched to clients.

DESCW V4 and the FRINGE database
FRINGE does not contain within its listing *all* acquired frames, as shown in the DESCW frame listing, and so technically does not provide a fully exhaustive pair listing. The two systems do not correspond.

Orbit control
Differential interferometry requires tight orbit control so that the SAR antenna is near enough exactly at the same place relative to the ground at each repeat acquisition of a footprint (within 50m, better if DEM resolution is coarse). This would not only be more costly to achieve, but is not in the mission plan of ESA, who also need to cater for those wishing to generate InSAR DEMs, requiring much longer Bperps. For subsidence mapping, reducing the variety of InSAR pairs with smaller Bperps decreases the chance of generating positive results.

Data continuity?
ERS-2 is destined to be switched off sometime in the next couple of years, to be replaced by Envisat. This will be the end of a ten year ERS SAR data archive, with no practical pairing to future Envisat ASAR data. For subsidence mapping, it will take at least 2 years for a useful ASAR data archive to develop (presuming Envisat launches and operates successfully). NPA does not know what the period of overlap might be, if there is any at all, between ERS and Envisat operations. It is likely that within the next 5 to 10 years there will be a plethora of SAR missions and data, some of which might be VHR, to service developing subsidence map markets. It is the first few years after ERS that could look a little thin (though RADARSAT-2 should be launched).

10.3: Forecast

There is a significant market seen for ERS InSAR subsidence map products in the mid-term, though failing data continuity, just when the market is developing could present problems. By the number of planned SAR missions, all with InSAR borne in mind, the longer-term prospects for subsidence mapping using space-based InSAR look promising.

Real markets are becoming visible, as confidence in the capability of ERS InSAR grows – from both the customer's *and* producer's point of view. The momentum is growing in Arizona over both Tucson and Phoenix, and NPA now has the a seal of approval from Houston's HGCSD.

This momentum is to be continued by the significant promotional support won by NPA from the CEO in their EO Product and Development and Marketing initiative. A 6-month project entitled *CivInSAR Subsidence Mapping*, starting January 1999, will pay for the integration of the SWUS results with other spatial data of direct concern to subsidence risk managers on the ground, professionally packaging the products into versatile and accessible information. The funding also allows NPA to make further promotional visits to developing markets in the US.

The comprehensive distribution of positive US results generated from this ESA-funded project now makes a convincing and unique story, difficult to ignore by those responsible for subsidence mapping.

It is hoped that the work resulting from the *CivInSAR Subsidence Mapping* will provide the final kick-start required to establish reliable sales in the US.

NPA also anticipates a developing market for the use of radar corner reflector arrays in combination with ERS InSAR to provide point sample displacement information over sights normally constrained by poor coherence or inadequate spatial resolution. This work is currently being progressed by two independent, large-scale projects.

11: RECOMMENDATIONS

The project has clearly demonstrated a commercial opportunity for the application of ERS InSAR. Full potential is, however, curtailed and limited by a number of obstacles. Some of these are determined by inherent system design and would be too costly to remove. Others are simpler, and might involve minor modifications to existing systems, or even just changes in attitude. The following list makes some practical recommendations to ESA to improve the commercial potential of ERS InSAR.

11.1: Improving data access

- Priority should be given to commercial data orders. Delay should be no more than 14 days from order to receipt of data.
- Improve quality control of data products leaving ESA-ESRIN.
- Provide for internet download of SAR data from archives.
- Online data ordering directly through data archive browser (*e.g.* internet shopping with automatic email confirmation).
- DESCW search results need to accurately reflect what data is actually available (*e.g.* data listed as OK is found to contain missing lines).
- The FRINGE database should be accurately maintained, with a maximum 14-day delay for inclusion of latest acquisitions. There should be accurate correspondence between DESCW and FRINGE.
- Resolve inconsistencies in acquisition timing data given in headers (*e.g.* along-track timing errors in meta-data for scenes acquired by Prince Albert ground station).
- The clearer atmosphere during the night reduces the chance of signal refraction, and night-time, ascending data is preferable for InSAR work. Though there might be power constraints on building a comprehensive ascending data archive, is as much ascending data acquired as possible? Could the SWUS be targeted in particular for ascending data?
- Same-season acquisition improves coherence over multi-year separations. More effort might be made to program for same-season datasets over regions with commercial potential.
- ERS should be programmed to acquire as much data as possible over the SWUS to improve chances of matching ideal interferometric pairs in terms of Bperp, temporal separation and epoch.

11.2: Improving hit-rate of positive results

- To reduce the ambiguities caused by atmospheric refraction, there needs to be operational and economic access to some climatological / precipitation / cloud-cover and type database, contemporaneous with InSAR data acquisition.
- Ideally, spatial data on prevailing atmospheric conditions would be supplied with each InSAR dataset to provide indications as to possible ambiguities (analogous to the percentage of cloud-cover quoted with SPOT data).

- A more informed estimation can be made of likely image coherence levels if prevailing landcover characteristics are known. Ideally, contemporaneous (or same time of year) optical landcover imagery should be accessible. The project tried making use of TM QLs for this purpose, but the coarse spatial resolution prevented the extraction of any useful information.
- Again, for estimation of coherence levels, a non-Tandem Mission coherence quicklook reference would be useful to show average coherence levels over key regions for temporal separations of 6 months, 1 year and multi-year.

11.3: General recommendations

- Current inconsistencies in the ERS/ESA system means that a close working relationship is often useful between the practitioner of ERS InSAR and ESA-ESRIN staff. There needs to be a more coherent and streamlined policy to support and sustain commercial ERS InSAR for displacement mapping (*e.g.* policy on InSAR datasets sold that yield insufficient coherence to generate positive results).
- The benefits of conducting this project to both NPA and ESA are clear. ESA-ESRIN should continue to be pro-active in supporting this kind of demonstration work and the value-adding required to realise the operational potential of their products. On this, NPA would invite another ESA contract, this time aimed at commercialising the use of InSAR in conjunction with radar corner reflectors, *e.g.* along the subsidence-prone route of the UK Channel Tunnel rail link.
- During this project, NPA has expended considerable time and effort in the identification of actual and potential ERS InSAR markets. It is understood that while ESA may wish to divulge the generalities of the project's success and findings to third parties, NPA would strongly resist any dissemination of specific detail.

12: CONCLUSIONS

This 12 month project has been significant in progressing the operational application of ERS InSAR to ground displacement mapping. There is often scepticism when citing truly commercial applications of remote sensing, as so few genuinely exist. Space-based InSAR is a complicated technology, and its general application to subsidence mapping is severely restricted. However, this does not detract from the fact that in some environmental and geographic regions, results of the technique match the requirements closely of subsidence risk managers on the ground.

The positive processing rate of 69% overall shows that NPA is becoming adept at estimating the feasibility of application before processing any data. This success rate would be higher if ideal datasets were always available in terms of epoch, temporal separation and Bperp.

It is essential to commercialism that accurate databases are maintained of available InSAR pairings, and that distribution of ordered data is reliable and timely. A number of the difficulties experienced in data access processes have been highlighted.

There is some concern over data continuity. Over the next couple of years, just as markets might be maturing, ERS-2 will be switched off, to be replaced, hopefully, by Envisat. This will end the ten year SAR data archive, with no practical pairing to future Envisat ASAR data. Trust has to be placed in the continuing usefulness of 'historic' subsidence maps generated from ERS and the successes of both Envisat and RADARSAT-2, that the growing credibility and reliability perceived by markets in the InSAR technique continues without hiatus.

Overall, the project has been invaluable in supporting NPA to realise its commercial objectives for the marketing of ERS InSAR products. It has identified a viable market, provided a credible portfolio of results that demonstrate the technique's reliability, and it has helped refine NPA's InSAR processing chain to handle the diversity of problems associated. NPA trusts that ESA's objectives have also been fulfilled by seeing a new and viable commercial market for ERS products demonstrated, and by showing that the Agency is able to successfully stimulate market development by external support of the value-adding industry.

ESA Contract 12536/97/I-HGE

End-to-end performance evaluation of SAR subsidence monitoring system

APPENDIX to Final Report
PROCESSING RESULTS & GRAPHICS

December 1998

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FINAL REPORT APPENDIX: PROCESSING RESULTS & GRAPHICS

This Appendix contains the processing output for 39 interferometric datasets covering 26 test-sites. Included with the graphical results for each site, are the *Test-Site Identification Report* and *Processing Summary Report*. Sites are arranged by state in the US (and Mexico), then by other countries.

USA and Mexico

Arizona

California

Nevada

New Mexico

Texas

Utah

Mexico

NON-USA

Australia

Italy

Eloy/Picacho, Arizona **OVERALL RATING: 67%**

1. Marketability *Rating: Medium*

The Eloy/Picacho basin is the first location in Arizona where subsidence was discovered, the area is also prone to fissuring. The CAP canal, extending for 335 miles from Lake Havasu to Tucson has been identified as being under threat from subsidence and fissuring when it passes through the Eloy basin.

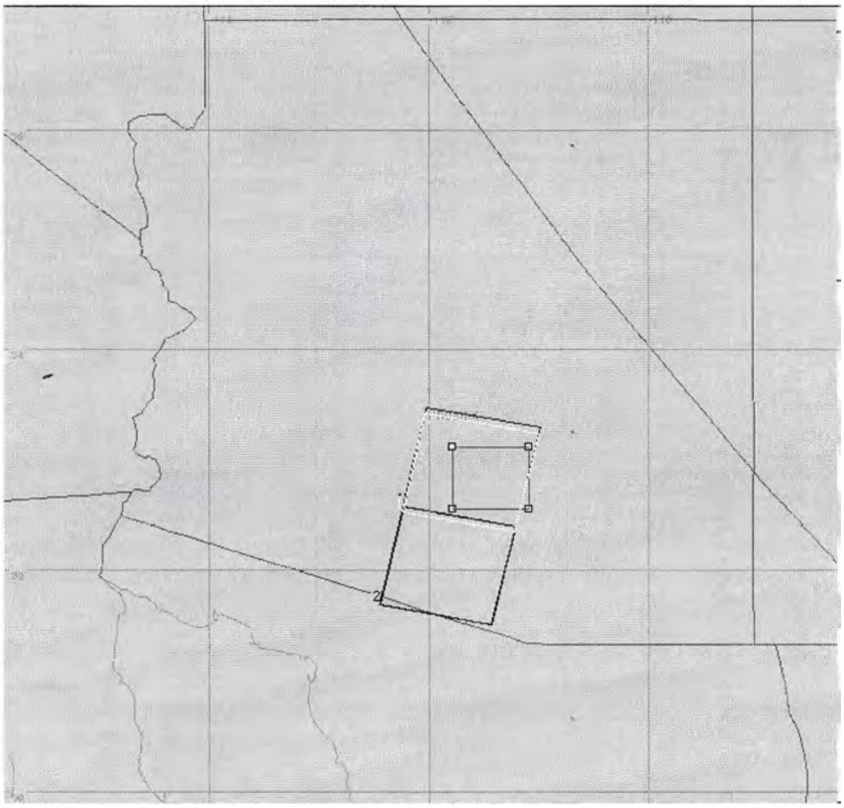
2. Subsidence category

Groundwater extraction.

3. Geographical extents and optimal ERS coverage

The extents of recorded subsidence in the Eloy/Picacho basin are approximately:

Longitude:	32° 32' N - 33° 6' N	(60 km)
Latitude:	111° 5' W - 111° 46' W	(60 km)



4. Socio-economic effects of subsidence

Unknown.

5. Customer / contact

Mike Carpenter, Hydrologist, USGS Tucson, AZ. E-mail: mccarp@usgs.gov

Stanley Leake, Research Hydrologist, Tucson, AZ E-mail: saleake@usgs.gov

Donald Pool, Hydrologist, Tucson, AZ E-mail: drpool@usgs.gov

Daniel Evans, Hydrologist, Tucson, AZ E-mail: dwevans@usgs.gov

Maurice Tatlow, Arizona Dept. of Water Resources, Phoenix, AZ
E-mail: matatlow@ADWR.state.az.us

6. Subsidence rate/amount *Rating: Low*

Subsidence was first observed in Arizona at Eloy. About 675 square miles of the area were determined to be affected by 1948, more than 15 feet of subsidence was evident by 1985.

7. Ground-truth available *Rating: Medium*

Seasonal maximum subsidence occurs September to October. Compaction recorders are in operation and results should be available soon.

8. Land cover *Rating: Good*

Arid agricultural land with 2 urban areas (Eloy and Picacho).

9. ERS Data availability and status *Rating: High*

No suitable ascending pairs available.
Descending: 28 pairs with a perpendicular baselines less than 50m and a temporal separation greater than a year.

Receiving Station: Prince Albert

10. DEM availability

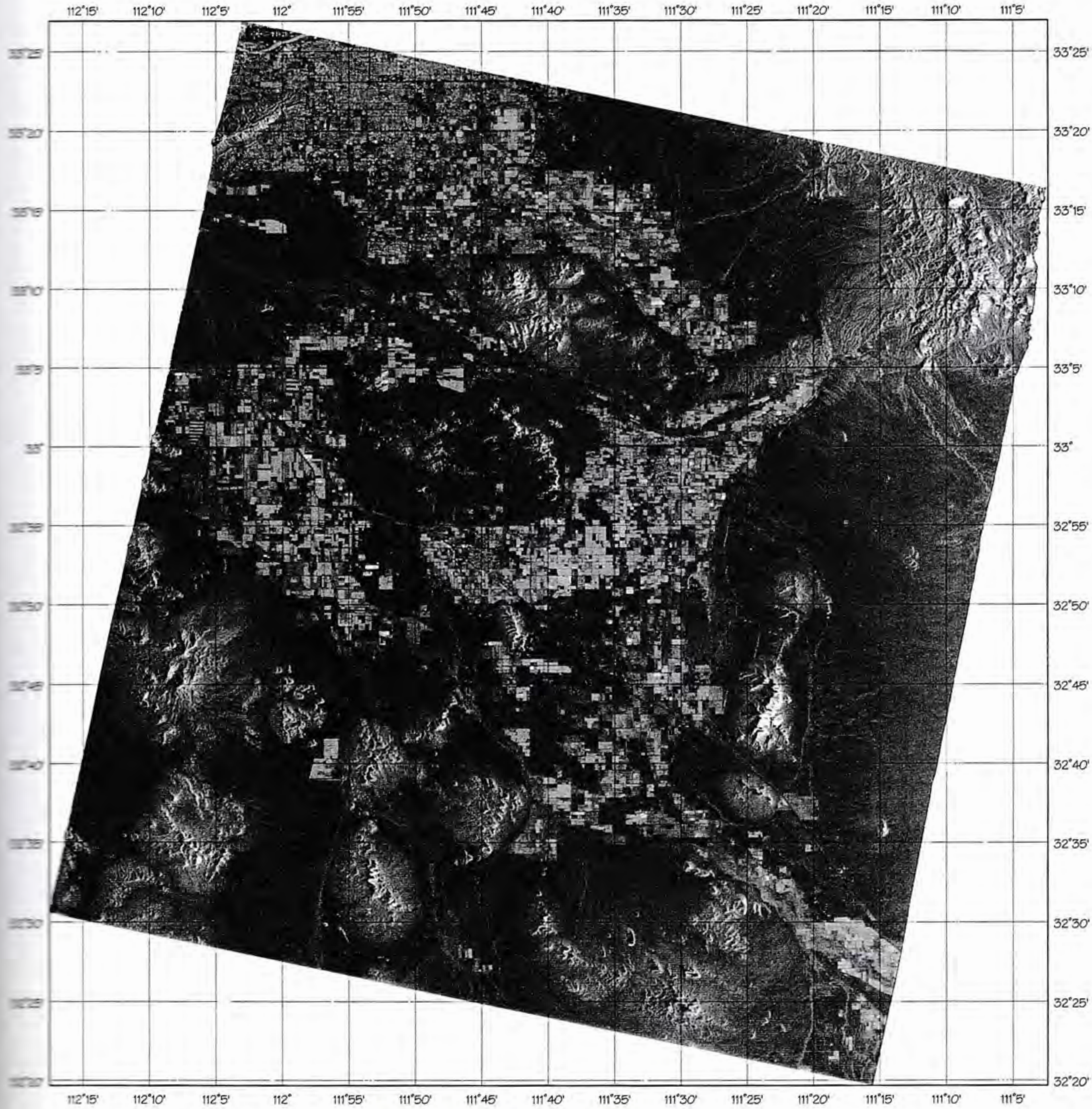
- USGS 1 arc second resolution xy and 20m z DEM available in 0.5° × 0.5° tiles.
  Cost approx. $100 for first tile, additional tiles much cheaper, coarse 1km resolution DEM.
- USGS 3 arc second resolution xy and 20m z DEM for the whole of the US held in-house.
- GTOPO-30 coarse 1km resolution DEM of variable quality held in house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in house yet.
- Tandem InSAR.

11. Processing status

Two differential interferograms produced.

Radar amplitude image for the Eloy/Picacho, Arizona area

ERS scene date: 19 September 1993



0 10 20 30 40 50 km

NPA SATELLITE MAPPING

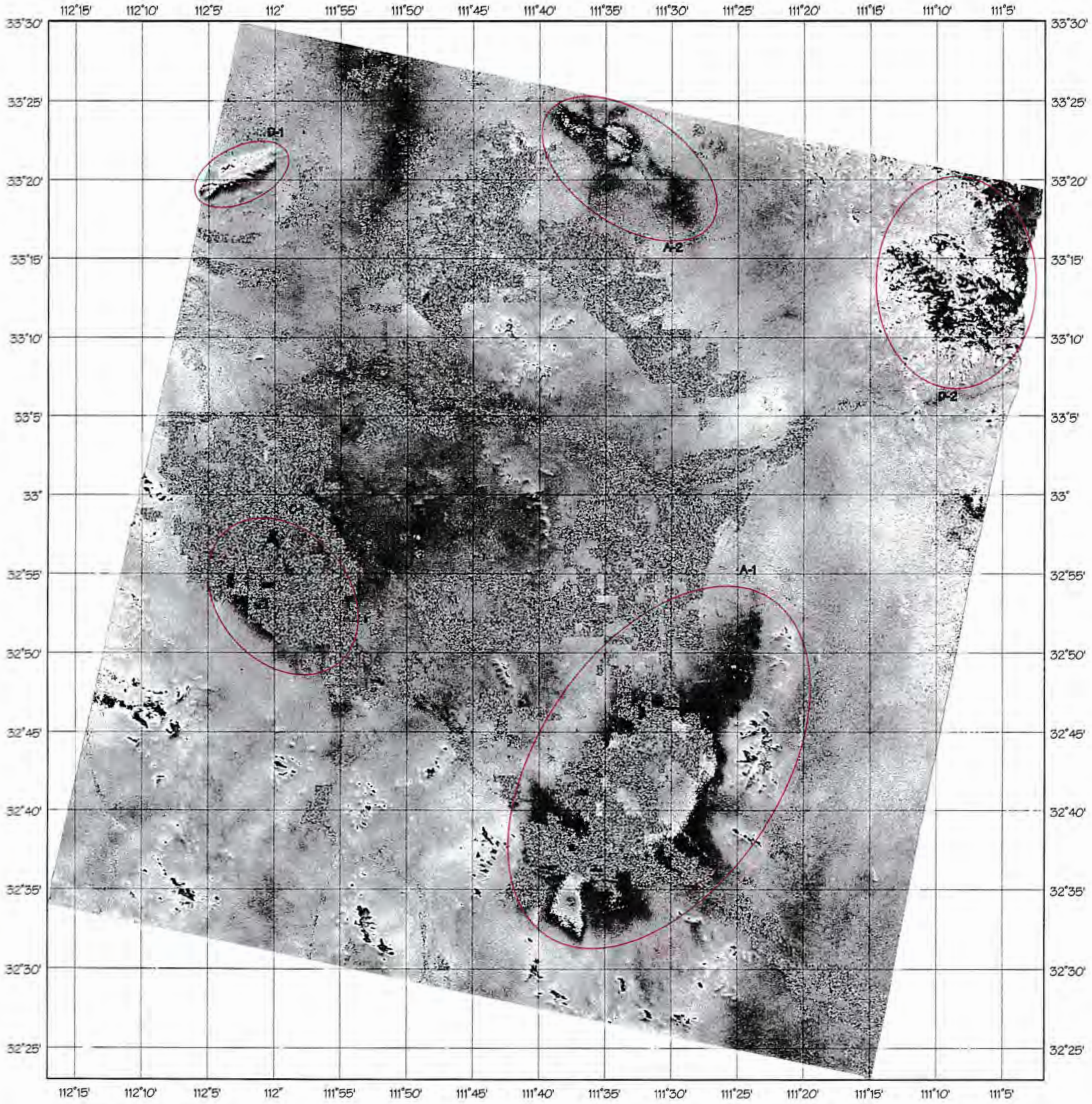
esa european space agency

Supported by DERA PHOENIX

Differential interferogram for the Eloy/Picacho, Arizona area

ERS scene dates: 18 October 1995 & 6 November 1996
Temporal separation: 1 year 1 month
Perpendicular baseline: 29.0 m
Altitude of ambiguity: 324.7 m

Rings indicate fringe features in this image



NPA SATELLITE MAPPING

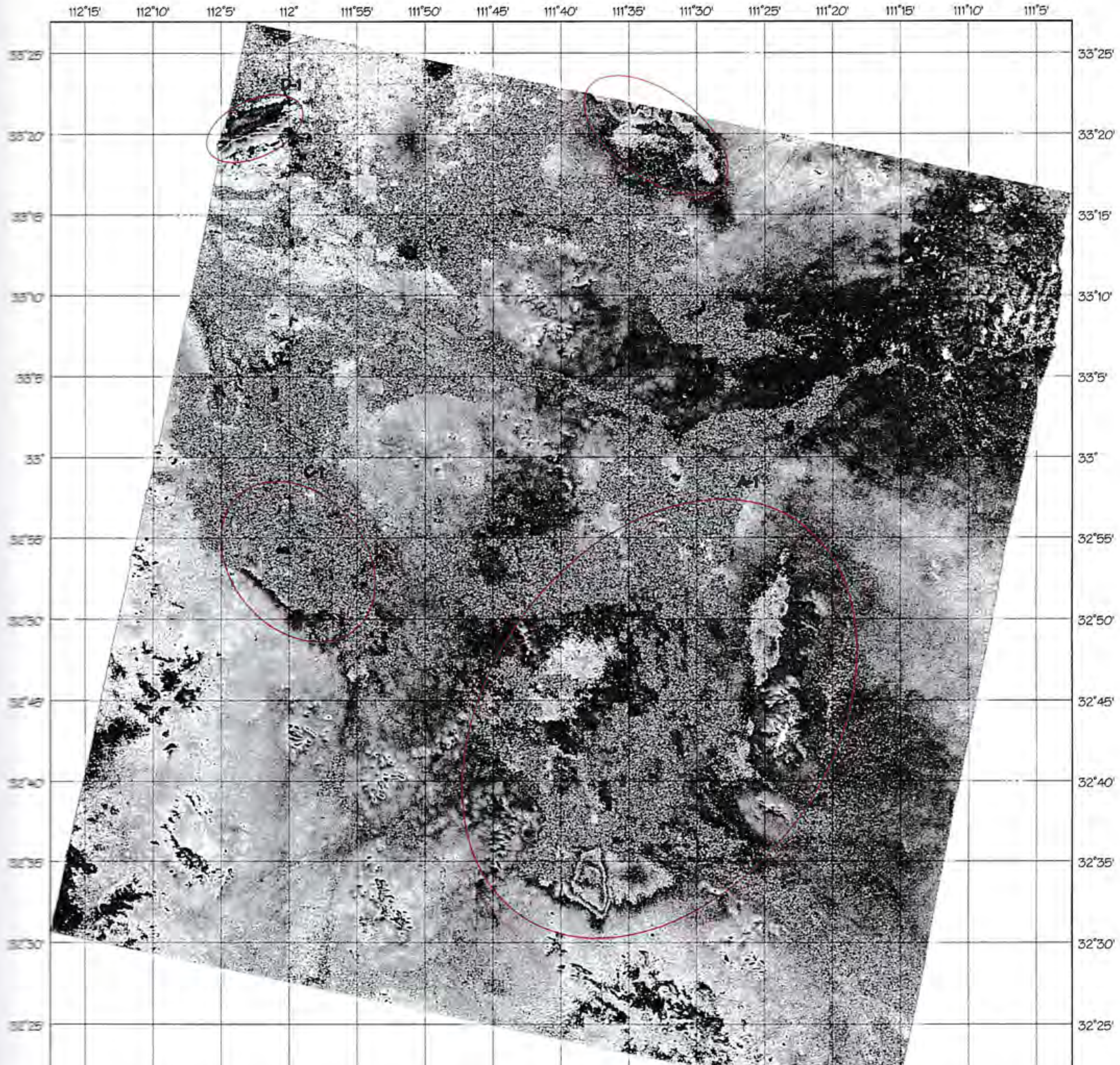
esa european space agency

Supported by DERA

Differential interferogram for the Eloy/Picacho, Arizona area

ERS scene dates: 19 September 1993 & 26 December 1995
Temporal separation: 2 years 3 months
Perpendicular baseline: 46.2 m
Altitude of ambiguity: 203.8 m

Rings indicate fringe features in this image



NPA SATELLITE MAPPING

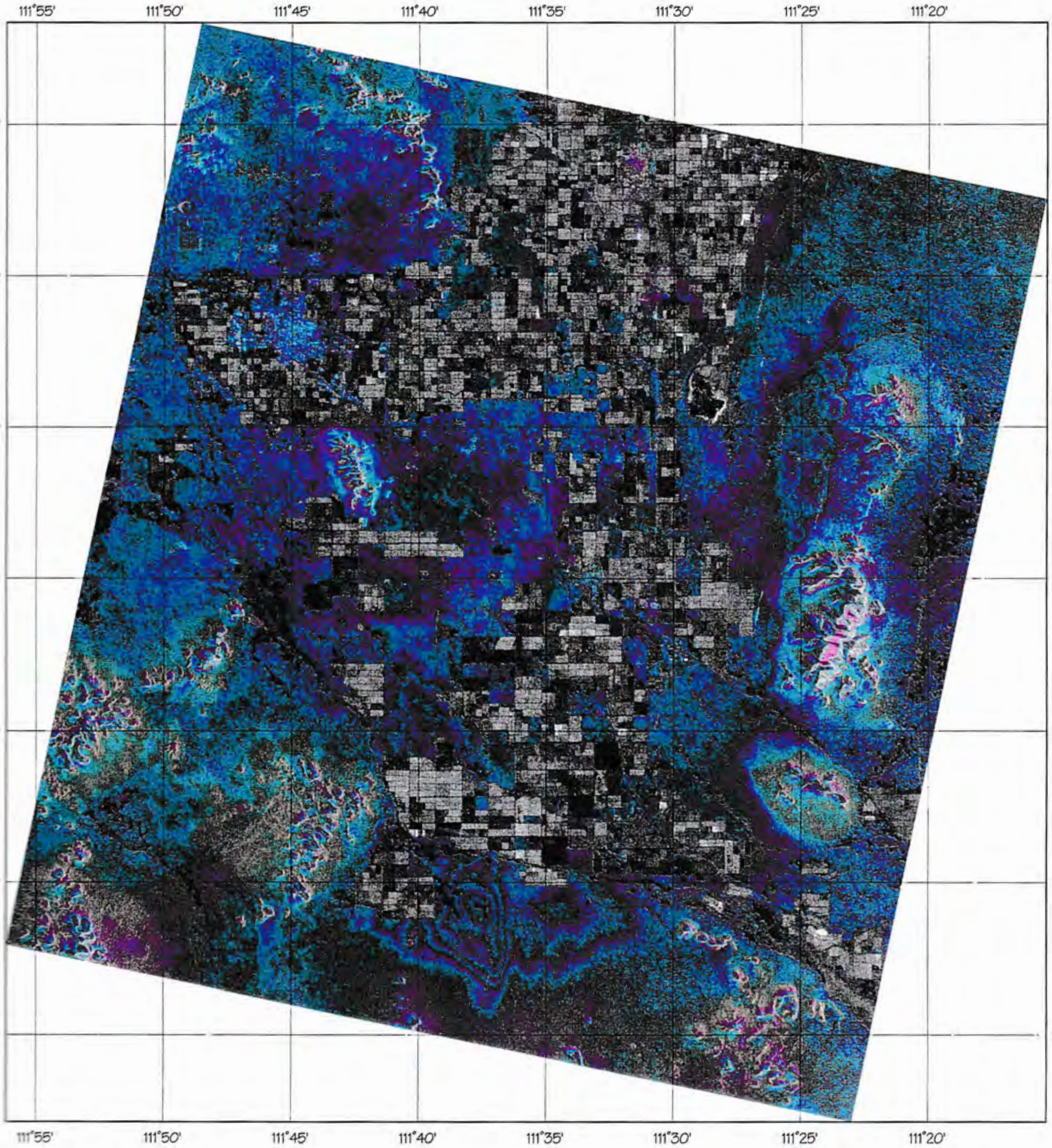
esa european space agency

Supported by DERA

Stacked interferograms for the Eloy/Picacho, Arizona area (Stacked, coherence masked differential interferograms over ERS radar amplitude image)

ERS scene dates: 19 September 1993, 26 December 1995, 18 October 1995 & 6 November 1996
Total temporal separation: 3 years 2 months
Overlap between the two interferograms: 2 months

Ground displacement per fringe cycle in ERS line of sight: 0 cm 1.4 cm 2.8 cm



0 5 10 15 20 25 km

NPA SATELLITE MAPPING

esa european space agency

Supported by DERA PHOENIX

SAR & InSAR Processing Summary Report — **Eloy/Picacho, Arizona: ELO_1 & ELO_2**

1. Image Acquisition Dates:	18/10/95, 6/11/96
2. Temporal Separation:	1 year 1 month
3. Processing Stage (1[int], 2[diff] or 3[full]):	3
4. DEM details, if used:	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. SLC Processing:	
(i) Scene centre lat/long:	33° 02' 06" N, 111° 37 45" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 107.0 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	32° 56' 55" N,111° 40' 32" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	98.4 km × 107.0 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	**Y**
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	29 m
(b) Derived from Precise State Vectors:	29.0 m
(iii) Altitude of Ambiguity:	324.7 m
(iv) Range × Azimuth extents:	99.0 km × 106.3 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	27.00
(ii) Standard Deviation:	17.68

9. Analysis/Interpretation of Results

Two interferometric data sets have been acquired and analysed covering the southwestern corner of the Phoenix metropolitan area, and the towns of Eloy, Picacho and Casa Grande, Arizona, USA. The two interferometric data sets have temporal separations of thirteen months and two years 3 months.

The data has been corrected for the effects of topography using a 100 m digital elevation model, and the georeferencing given by the lat/long grid is accurate to approx. 100 m. The coherence of the scene is generally good on both scenes, with the exception of land under cultivation. The differential interferograms exhibit a moderate degree of low frequency phase variation, of a magnitude of up to ½ a phase cycle. This is probably due to a combination of atmospheric effects.

The interferometric analysis reveals a pattern of continuing subsidence over the area. On the first 13-month separation interferogram two distinct regions of subsidence are apparent, labelled A1 and A2. Region A1 is to the East of Picacho, with a size of approximately 40 km by 15 km. Region A2 is to the South East of the Phoenix Metropolitan area, with a smaller geographic extent of around 20 km by 5 km, with several localised 'hotspots'. Both regions exhibit surface subsidence of order 3 cm over the 13-month interval between acquisitions.

This subsidence pattern is generally confirmed by the 27-month separation interferogram. The centre of region A1 is unfortunately largely incoherent, but the general extent of the subsidence can be seen clearly, with a 9cm 'hotspot' at the Southern side. Region A2 is also apparent on the second interferogram, although with comparable subsidence of 3cm despite the longer temporal separation, possibly suggesting that the rate of subsidence in this area is increasing (the epoch of the 27-month interferogram precedes that of the 13-month interferogram).

There is also a suggestion of subsidence in an extended region to the West of Casa Grande (region C1), of a smaller magnitude, in both interferograms. The loss of coherence associated with land cultivation here makes interpretation difficult however.

In this scene the topography changes abruptly and rises steeply over the rocky outcrops, increasing the sensitivity of the differential phase to the accuracy of the DEM. In this instance there appears to be a slight miss-registration of the DEM with the data in this scene, giving rise to a number of minor topographic phase artefacts, such as regions D1 and D2.

10. Conclusions/Recommendations

Category	Label	Co-ordinates	Comments
2 class A features	A1	32° 40' 50" N 111° 32' 39" W	Extended subsidence to the East of Picacho
	A2	33° 21' 2" N 111° 34' 3" W	Subsidence to the South East of the Phoenix Metropolitan area
1 class C feature	C1	32° 54' 4" N 111° 59' 42" W	Possible subsidence to the West of Casa Grande
2 class D features	D1	33° 20' 16" N 112° 2' 29" W	Processing artefact
	D2	33° 12' 44" N 111° 8' 5" W	Processing artefact

Categories: A *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/ Feature of interest*

SAR & InSAR Processing Summary Report **Eloy/Picacho, Arizona: ELO_3 & ELO_4**

1. **Image Acquisition Dates:**	19/9/93, 26/12/95
2. **Temporal Separation:**	2 years 3 months
3. **Processing Stage (1[int], 2[diff] or 3[full]):**	3
4. **DEM details, if used:**	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. **SLC Processing:**	
(i) Scene centre lat/long:	32° 53' 13"N, 111° 38' 21" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. **Ground-range PRI (Amplitude Image) Processing:**	
(i) Scene centre lat/long:	32° 53' 25" N,111° 41' 7" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	98.5 km × 107.1 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. **InSAR Processing**	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	42 m
(b) Derived from Precise State Vectors:	46.2 m
(iii) Altitude of Ambiguity:	203.8 m
(iv) Range × Azimuth extents:	98.9 km × 106.9 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. **Coherence Map Parameters**	
(i) Mean:	27.00
(ii) Standard Deviation:	17.68

9. Analysis/Interpretation of Results

Two interferometric data sets have been acquired and analysed covering the southwestern corner of the Phoenix metropolitan area, and the towns of Eloy, Picacho and Casa Grande, Arizona, USA. The two interferometric data sets have temporal separations of thirteen months and two years 3 months.

The data has been corrected for the effects of topography using a 100 m digital elevation model, and the georeferencing given by the lat/long grid is accurate to approx. 100 m. The coherence of the scene is generally good on both scenes, with the exception of land under cultivation. The differential interferograms exhibit a moderate degree of low frequency phase variation, of a magnitude of up to ½ a phase cycle. This is probably due to a combination of atmospheric effects.

The interferometric analysis reveals a pattern of continuing subsidence over the area. On the first 13-month separation interferogram two distinct regions of subsidence are apparent, labelled A1 and A2. Region A1 is to the East of Picacho, with a size of approximately 40 km by 15 km. Region A2 is to the South East of the Phoenix Metropolitan area, with a smaller geographic extent of around 20 km by 5 km, with several localised 'hotspots'. Both regions exhibit surface subsidence of order 3 cm over the 13-month interval between acquisitions.

This subsidence pattern is generally confirmed by the 27-month separation interferogram. The centre of region A1 is unfortunately largely incoherent, but the general extent of the subsidence can be seen clearly, with a 9cm 'hotspot' at the Southern side. Region A2 is also apparent on the second interferogram, although with comparable subsidence of 3cm despite the longer temporal separation, possibly suggesting that the rate of subsidence in this area is increasing (the epoch of the 27-month interferogram precedes that of the 13-month interferogram).

There is also a suggestion of subsidence in an extended region to the West of Casa Grande (region C1), of a smaller magnitude, in both interferograms. The loss of coherence associated with land cultivation here makes interpretation difficult however.

In this scene the topography changes abruptly and rises steeply over the rocky outcrops, increasing the sensitivity of the differential phase to the accuracy of the DEM. In this instance there appears to be a slight miss-registration of the DEM with the data in this scene, giving rise to a number of minor topographic phase artefacts, such as regions D1 and D2.

10. Conclusions/Recommendations

Category	Label	Co-ordinates	Comments
2 class A features	A1	32° 40' 50" N 111° 32' 39" W	Extended subsidence to the East of Picacho
	A2	33° 21' 2" N 111° 34' 3" W	Subsidence to the South East of the Phoenix Metropolitan area
1 class C feature	C1	32° 54' 4" N 111° 59' 42" W	Possible subsidence to the West of Casa Grande
2 class D features	D1	33° 20' 16" N 112° 2' 29" W	Processing artefact
	D2	33° 12' 44" N 111° 8' 5" W	Processing artefact

Categories: A *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/Feature of interest*

Phoenix, Arizona — OVERALL RATING: 73%

1. Marketability — *Rating: Good*

A major US urban centre. Maurice Tatlow on behalf of Arizona Dept. of Water Resources has expressed a great deal of interest in interferograms over Phoenix. The Arizona Dept. of Water Resources is in the process of deciding on the number of GPS stations to be funded in Phoenix. However they may be interested in diverting some of this money to commissioning interferometric studies over Phoenix.

2. Subsidence category

Ground water extraction.

3. Geographical extents and optimal ERS coverage

The extents of the Phoenix area are approximately:

Longitude:	111° 19' W - 112° 19' W	(45 km)
Latitude:	33° 42' N - 34° 42' N	(40 km)

4. Socio-economic effects of subsidence

Currently unknown.

5. Customer / contact

Mike Carpenter, Hydrologist, USGS Tucson, AZ. E-mail: mccarp@usgs.gov

Stanley Leake, Research Hydrologist, Tucson, AZ E-mail: saleake@usgs.gov

Donald Pool, Hydrologist, Tucson, AZ E-mail: drpool@usgs.gov

Daniel Evans, Hydrologist, Tucson, AZ E-mail: dwevans@usgs.gov

Maurice Tatlow, Arizona Dept. of Water Resources, Phoenix, E-mail: matatlow@ADWR.state.az.us

6. Subsidence rate/amount — *Rating: Low*

Subsidence of up to 17 feet has occurred in the period 1957-1991. We do not have information on the current rate of subsidence.

7. Ground-truth available — *Rating: Poor*

A new GPS campaign is to launched in the near future.

8. Land cover — *Rating: Good*

Major urban area, surrounded by arid land.

9. ERS Data availability and status — *Rating: High*

No suitable ascending pairs are available.
Descending:
15 pairs with perpendicular baselines less than 50m and a temporal separation greater than a year

Receiving Station: Prince Albert

10. DEM availability

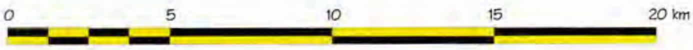
- USGS 1 arc second resolution xy and 20m z DEM available in 0.5° × 0.5° tiles.
  Cost approx. $100 for first tile, additional tiles much cheaper.
- USGS 3 arc second resolution xy and 20m z DEM for the whole of the US held in-house.
- GTOPO-30 coarse 1km resolution DEM of variable quality held in house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in house yet.
- Tandem InSAR.

11. Processing status

Two differential interferograms produced.

Radar amplitude image for the Luke Air Force Base and Glendale, Phoenix

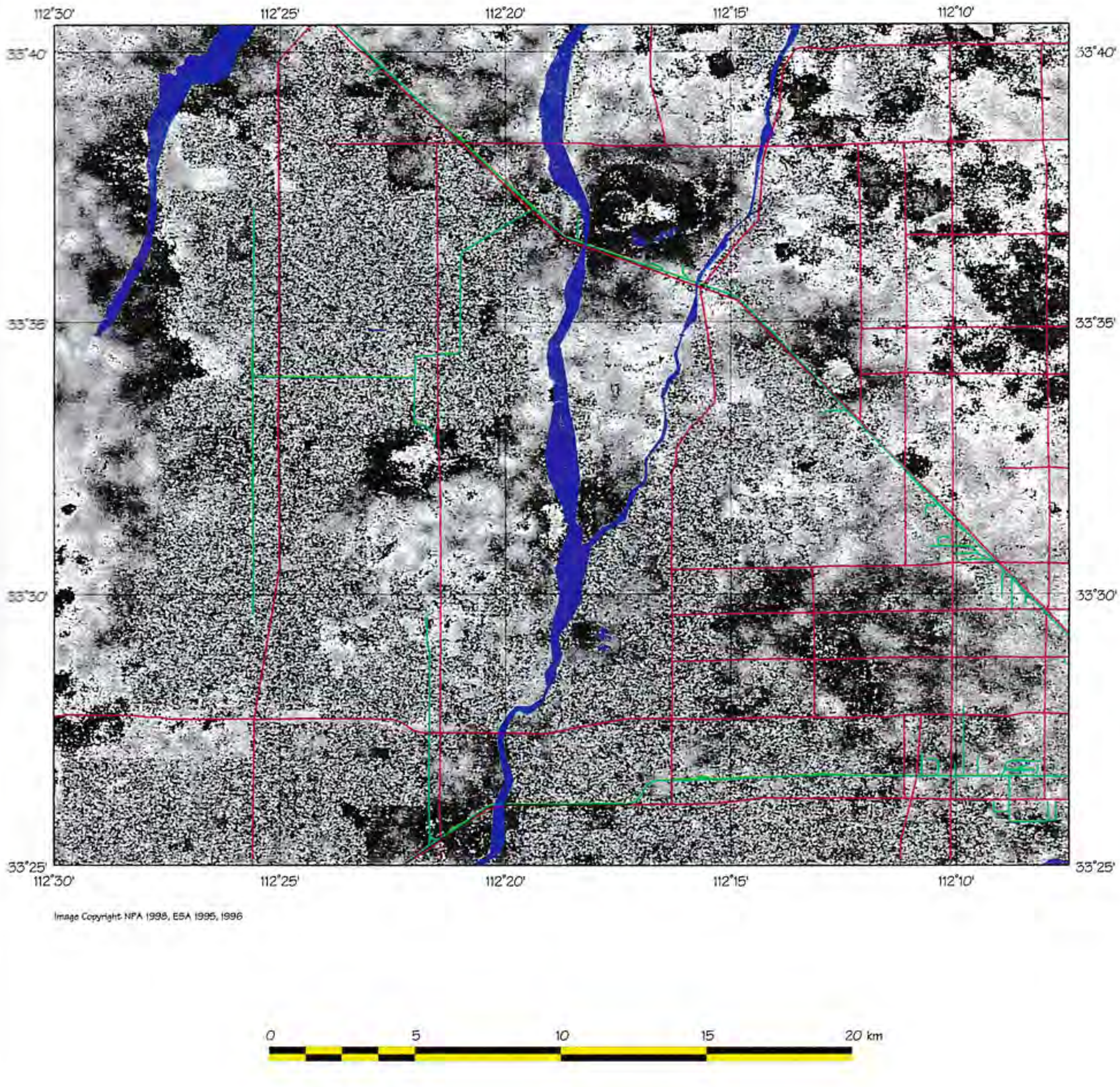
ERS scene date: 27 August 1995



Differential interferogram for the Luke Air Force Base and Glendale, Phoenix

ERS scene dates: 27 August 1995 & 12 August 1996
Temporal separation: 1 year
Perpendicular baseline: 32.8 m
Altitude of ambiguity: 287.1 m

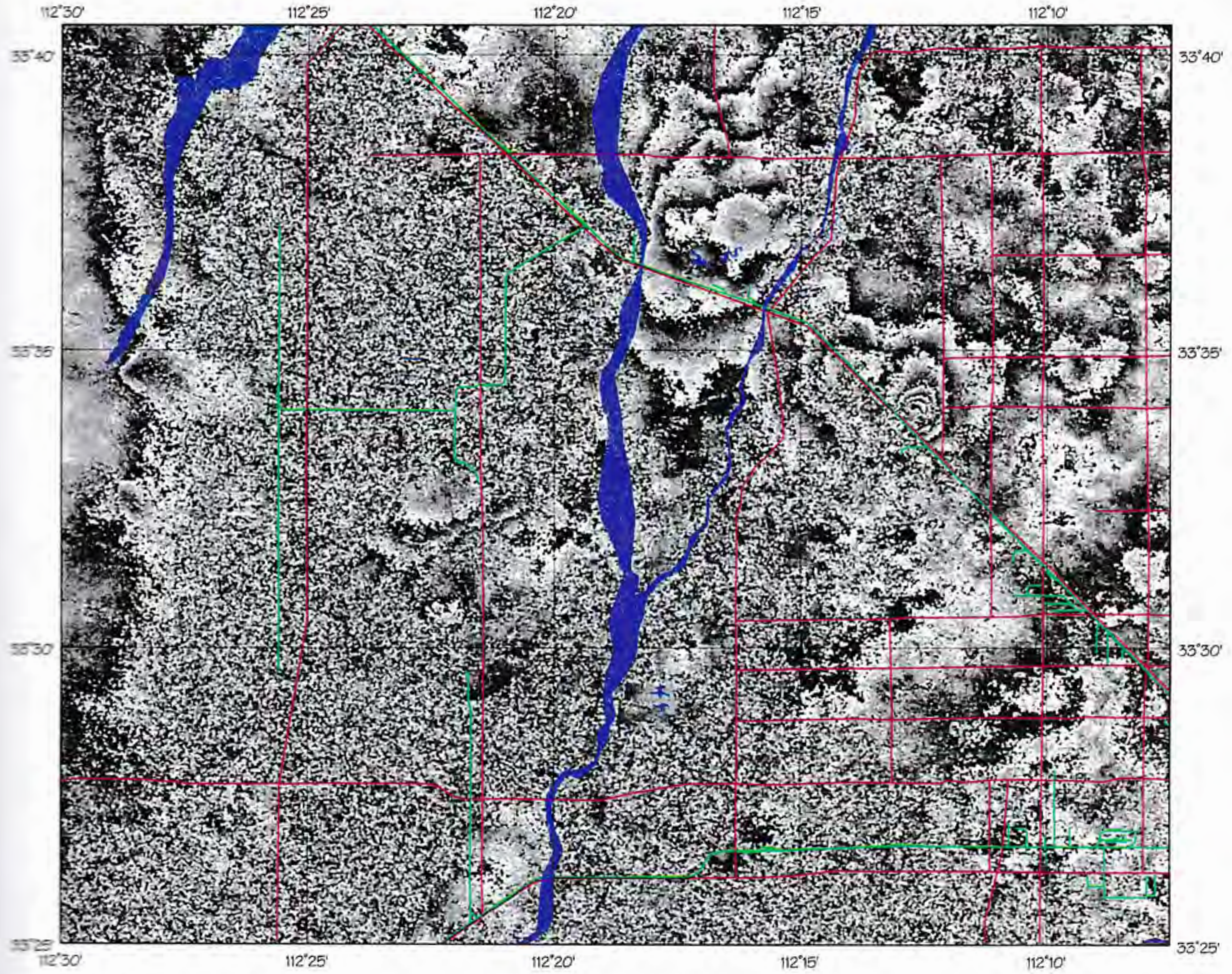
Key:
Red: Interstates and main highways
Blue: Water areas
Green: Railroads



Differential interferogram for the Luke Air Force Base and Glendale, Phoenix

ERS scene dates: 21 May 1993 & 16 September 1996
Temporal separation: 3 years 4 months
Perpendicular baseline: 11.9 m
Altitude of ambiguity: 791.3 m

Key:
Red: Interstates and main highways
Blue: Water areas
Green: Railroads



NPA
SATELLITE MAPPING
esa
european space agency
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PHOENIX

SAR & InSAR Processing Summary Report | **Phoenix, Arizona: PHO_1 & PHO_2**

1. Image Acquisition Dates:	27/8/95, 12/8/96
2. Temporal Separation:	1 year
3. Processing Stage (1[int], 2[diff] or 3[full]):	3
4. DEM details, if used:	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. SLC Processing:	
(i) Scene centre lat/long:	32° 21' 7" N, 112° 29' 6"W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	33° 35' 38" N,112° 12' 47"W
(ii) Full- (or sub-) scene Range × Azimuth extents:	99.0 km × 107.1 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	32 m
(b) Derived from Precise State Vectors:	32.8 m
(iii) Altitude of Ambiguity:	287.1 m
(iv) Range × Azimuth extents:	99.0 km × 106.7 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	3, 12
8. Coherence Map Parameters	
(i) Mean:	34.36
(ii) Standard Deviation:	20.07

9. Analysis/Interpretation of Results

Data Specifications

Figure 1

ERS interferogram, data acquired 27-Aug-95 and 12-Aug-96
Temporal separation: 1 year
Baseline: 33 metres
Altitude of ambiguity: 287 metres

Figure 2

ERS interferogram, data acquired 21-May-93 and 16-Sep-96
Temporal separation: 3 years 4 months
Baseline: 12 metres
Altitude of ambiguity: 791 metres

Figure 3

Radar amplitude image for 27-Aug-95

Two interferometric data sets have been acquired and analysed covering the Luke Air Force Base and the Western edge of the Phoenix metropolitan area in Arizona, USA. The data sets have temporal separations of approximately one and three years respectively.

The spatial separation between the repeat orbital passes (the 'baseline') is insignificant for the three-year acquisitions and small (approx. 30 metres) for the one-year acquisitions. The data has been corrected for the effects of topography using a 100 m digital elevation model, and the georeferencing given by the lat/long grid is accurate to approx. 100 m.

The interferometric analysis reveals a pattern of continuing subsidence over the area, with three distinct regions of subsidence. First, a 'hot spot' of radius approx. 1 km centred on the suburb of Glendale with evidence of subsidence over a more extended area to the North and East. Second, subsidence at a comparable rate but over a much more extended area (10 by 5 km) centred on Sun City (between the confluence of the Agua Fria and Skunk Creek). Third, in a region centred just North West of the Luke Air Force Base. The overall coherence in this last region is poor because it is cultivated land. The pattern of fringes over the Luke Air Force Base is suggestive of a more extended subsidence over the region of poor coherence (speckly noise) as suggested by the fringe cycle to the West of the scene.

Figure 1 (1-year separation, 30 m baseline) is a presentation of the interferometric phase difference between acquisitions. On the 1-year separation the areas of subsidence are noticeable with around 1 phase cycle (approx. 3 cm of vertical displacement). While statistically significant, these localised phase variations are difficult to distinguish by eye from other phase noise (arising from e.g. atmospheric/ionospheric effects), and Figure 2 (3-year separation, 10 m baseline) should be contrasted with Figure 1. The overall coherence between the data sets is reduced as a consequence of the extended temporal separation, but remaining good over the urban and rocky areas, but with the effects of subsidence much more pronounced. Each of the three regions is seen to be subsiding at a rate of around 2-3 cm per year.

10. Conclusions/Recommendations

Category	Grid reference	Comments
A	112° 13' W, 33° 34' N	Localised subsidence in Glendale (3 cm/year)
A	112° 17' W, 33° 37' N	Generalised subsidence around Sun City (2.8 cm/year)
B	112° 23' W, 33° 33' N	Generalised subsidence around Luke Air Force Base (2-3 cm/year)

Categories: A *Definite, large-scale subsidence*

B *Probable/smaller-scale subsidence over a larger area*

C *Possible subsidence over a larger area*

D *Processing artefact/Feature of interest*

SAR & InSAR Processing Summary Report **Phoenix, Arizona: PHO_3 & PHO_4**

1. Image Acquisition Dates:	21/5/93, 16/9/96
2. Temporal Separation:	3 years 4 months
3. Processing Stage (1[int], 2[diff] or 3[full]):	3
4. DEM details, if used:	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. SLC Processing:	
(i) Scene centre lat/long:	33° 34' 34" N, 112° 10' 44"W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	33° 34' 40" N, 112° 13' 3" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	99.3 km × 107.1 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	6 m
(b) Derived from Precise State Vectors:	11.9 m
(iii) Altitude of Ambiguity:	791.3 m
(iv) Range × Azimuth extents:	99.0 km ×104.9 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	19.63
(ii) Standard Deviation:	14.11

9. Analysis/Interpretation of Results

Data Specifications

Figure 1

ERS interferogram, data acquired 27-Aug-95 and 12-Aug-96
Temporal separation: 1 year
Baseline: 33 metres
Altitude of ambiguity: 287 metres

Figure 2

ERS interferogram, data acquired 21-May-93 and 16-Sep-96
Temporal separation: 3 years 4 months
Baseline: 12 metres
Altitude of ambiguity: 791 metres

Figure 3

Radar amplitude image for 27-Aug-95

Two interferometric data sets have been acquired and analysed covering the Luke Air Force Base and the Western edge of the Phoenix metropolitan area in Arizona, USA. The data sets have temporal separations of approximately one and three years respectively.

The spatial separation between the repeat orbital passes (the 'baseline') is insignificant for the three-year acquisitions and small (approx. 30 metres) for the one-year acquisitions. The data has been corrected for the effects of topography using a 100 m digital elevation model, and the georeferencing given by the lat/long grid is accurate to approx. 100 m.

The interferometric analysis reveals a pattern of continuing subsidence over the area, with three distinct regions of subsidence. First, a 'hot spot' of radius approx. 1 km centred on the suburb of Glendale with evidence of subsidence over a more extended area to the North and East. Second, subsidence at a comparable rate but over a much more extended area (10 by 5 km) centred on Sun City (between the confluence of the Agua Fria and Skunk Creek). Third, in a region centred just North West of the Luke Air Force Base. The overall coherence in this last region is poor because it is cultivated land. The pattern of fringes over the Luke Air Force Base is suggestive of a more extended subsidence over the region of poor coherence (speckly noise) as suggested by the fringe cycle to the West of the scene.

Figure 1 (1-year separation, 30 m baseline) is a presentation of the interferometric phase difference between acquisitions. On the 1-year separation the areas of subsidence are noticeable with around 1 phase cycle (approx. 3 cm of vertical displacement). While statistically significant, these localised phase variations are difficult to distinguish by eye from other phase noise (arising from e.g. atmospheric/ionospheric effects), and Figure 2 (3-year separation, 10 m baseline) should be contrasted with Figure 1. The overall coherence between the data sets is reduced as a consequence of the extended temporal separation, but remaining good over the urban and rocky areas, but with the effects of subsidence much more pronounced. Each of the three regions is seen to be subsiding at a rate of around 2-3 cm per year.

10. Conclusions/Recommendations

Category	Grid reference	Comments
A	112° 13' W, 33° 34' N	Localised subsidence in Glendale (3 cm/year)
A	112° 17' W, 33° 37' N	Generalised subsidence around Sun City (2.8 cm/year)
B	112° 23' W, 33° 33' N	Generalised subsidence around Luke Air Force Base (2-3 cm/year)

Categories: A *Definite, large-scale subsidence*

B *Probable/smaller-scale subsidence over a larger area*

C *Possible subsidence over a larger area*

D *Processing artefact/Feature of interest*

Tombstone, Arizona **OVERALL RATING: 73%**

1. Marketability *Rating: Medium*

A US test site currently suffering form subsidence problems.

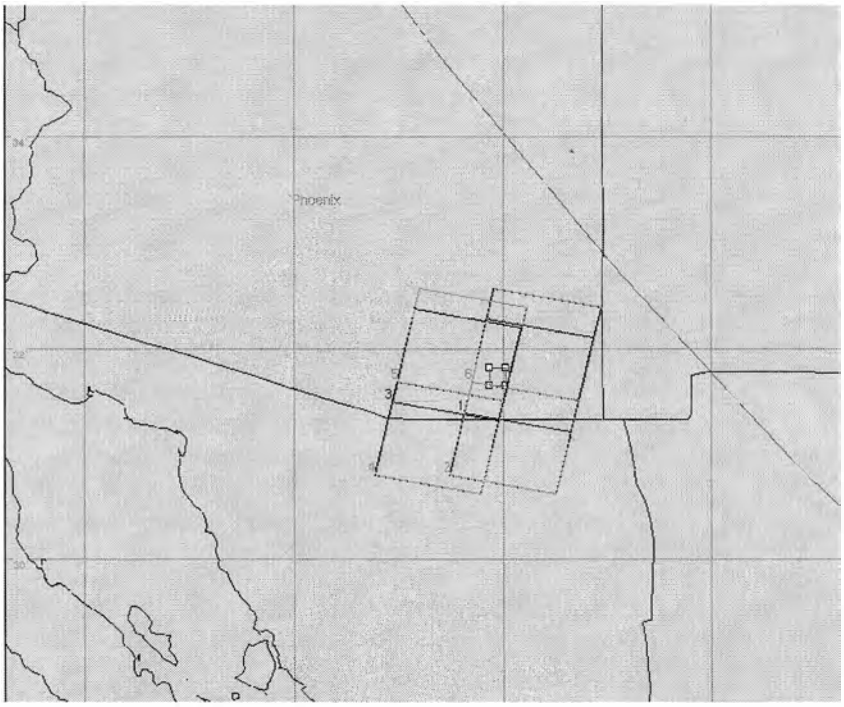
2. Subsidence category

Silver mine collapse.

3. Geographical extents and optimal ERS coverage

The extent of the Tombstone area are:

Longitude:	109° 58' W - 110° 7' W	(15 km)
Latitude:	31° 39' N - 31° 48' N	(15 km)



4. Socio-economic effects of subsidence

Currently unknown.

5. Customer / contact

Mike Carpenter, Hydrologist, USGS Tucson, AZ. E-mail: mccarp@usgs.gov

6. Subsidence rate/amount — Rating: Medium

A 60 ft diameter area was sinking at a rate of half an inch a day as a result of the collapsing of an abandoned silver mine.

7. Ground-truth available — Rating: Poor

Currently unknown.

8. Land cover — Rating: Good

Small urban area surrounded by arid land.

9. ERS Data availability and status — Rating: High

No suitable ascending frames available.
Descending frames:

1. (Area of interest in SW corner of scene) 15 pairs with perpendicular baselines less than 50m and a temporal separation greater than a year

2. (Area of interest in SE corner of scene) 10 pairs with perpendicular baselines less than 50m and a temporal separation greater than a year

Receiving station: Prince Albert

10. DEM availability

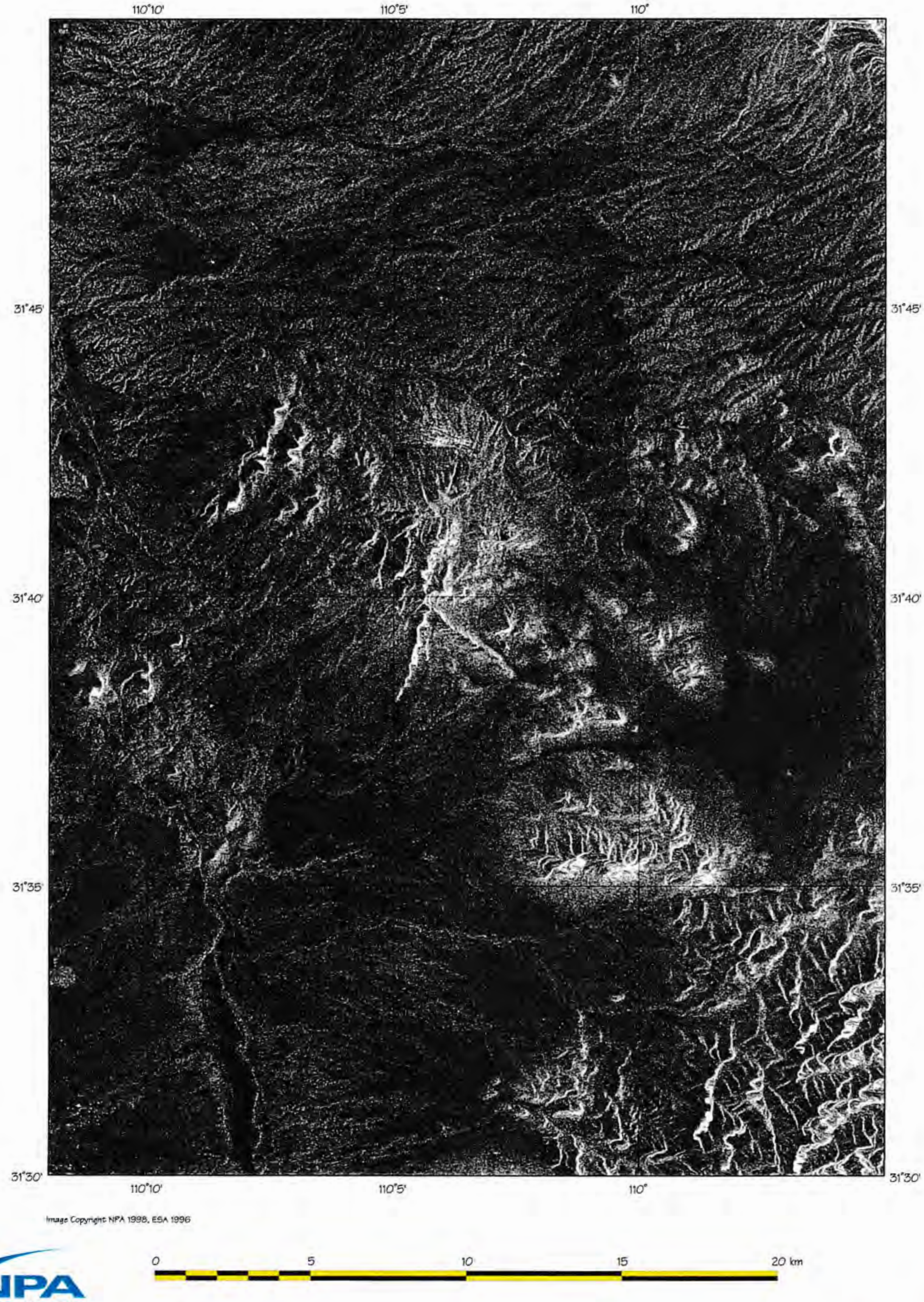
- USGS 1 arc second resolution xy and 20m z DEM available in 05° × 0.5° tiles.
  Cost approx. $100 for first tile, additional tiles much cheaper.
- USGS 3 arc second resolution xy and 20m z DEM for the whole of the US held in-house.
- GTOPO-30 coarse 1km resolution DEM of variable quality held in-house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in-house yet.
- Tandem INSAR.

11. Processing status

Two differential interferograms produced.

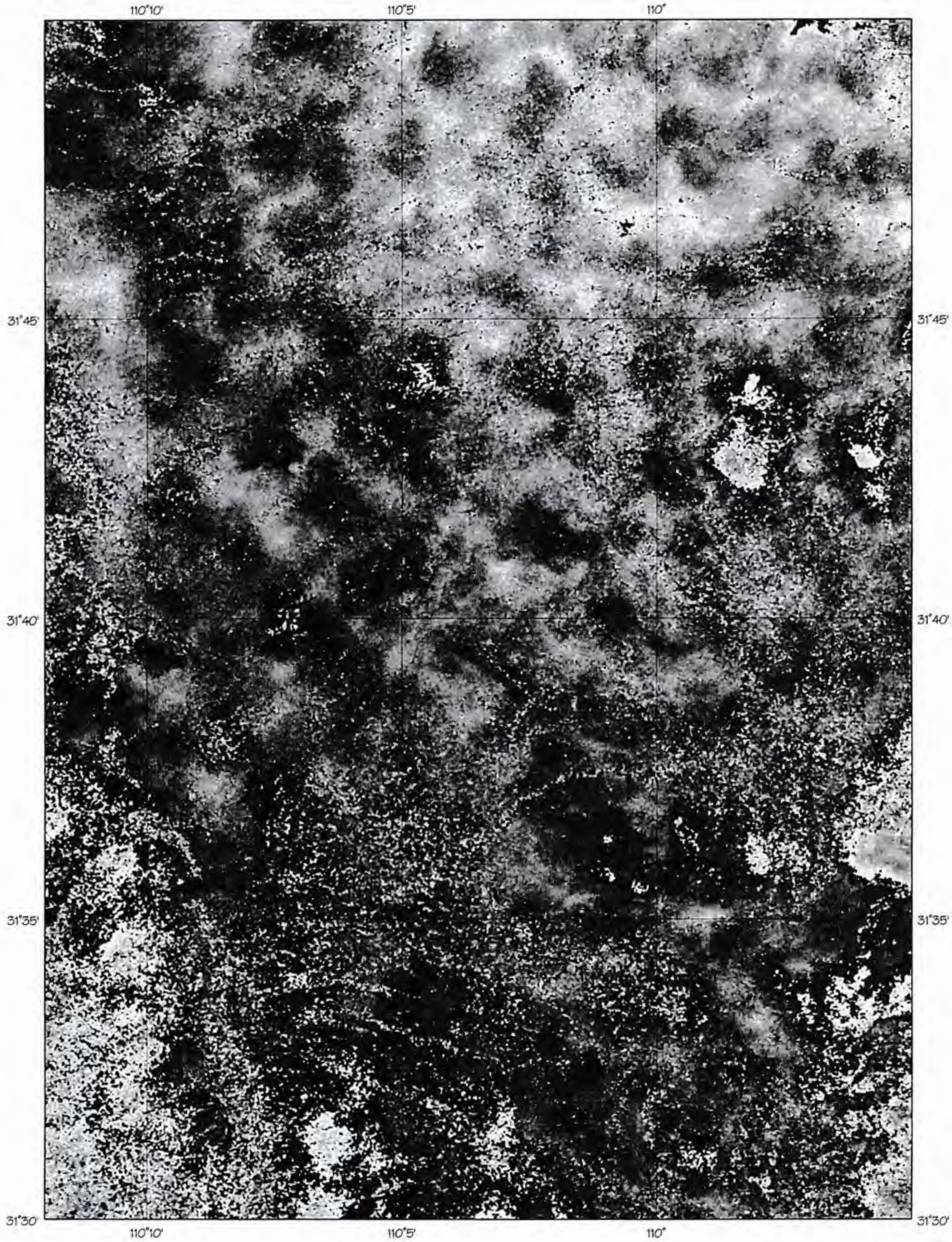
Radar amplitude image for the Tombstone, Arizona area

ERS scene date: 9 January 1996



Differential interferogram for the Tombstone, Arizona area

ERS scene dates: 17 October 1992 & 25 September 1995
Temporal separation: 2 years 11 months
Perpendicular baseline: 23.3 m
Altitude of ambiguity: 404.1 m



NPA SATELLITE MAPPING

esa european space agency

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Differential interferogram for the Tombstone, Arizona area

ERS scene dates: 9 January 1996 & 4 March 1997
Temporal separation: 1 year 2 months
Perpendicular baseline: 44.0 m
Altitude of ambiguity: 214.0 m

0 5 10 15 20 km

NPA SATELLITE MAPPING

esa european space agency

Supported by DERA

SAR & InSAR Processing Summary Report	**Tombstone, Arizona: TOM_1 & TOM_2**

1. **Image Acquisition Dates:**	17/10/92, 25/9/95
2. **Temporal Separation:**	2 years 11 months
3. **Processing Stage (1[int], 2[diff] or 3[full]):**	2
4. **DEM details, if used:**	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. **SLC Processing:**	
(i) Scene centre lat/long:	31° 45' 04" N, 109° 45' 33"W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. **Ground-range PRI (Amplitude Image) Processing:**	
(i) Scene centre lat/long:	31° 46' 26"N,109° 48' 28" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	97.2 km × 107.3 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. **InSAR Processing**	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	31 m
(b) Derived from Precise State Vectors:	23.3 m
(iii) Altitude of Ambiguity:	404.1 m
(iv) Range × Azimuth extents:	97.5 km × 105.3 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. **Coherence Map Parameters**	
(i) Mean:	18.20
(ii) Standard Deviation:	13.69

9. Analysis/Interpretation of Results

Data Specifications - Interferogram A
ERS acquisitions: 17-Oct-92 and 25-Sep-95
Temporal separation: 2 years 11 months
Perpendicular baseline: 25 m

Data Specifications - Interferogram B
ERS acquisitions: 09-Jan-96 and 04-Mar-97
Temporal separation: 1 year 2 months
Perpendicular baseline: 44 m

Good coherence is obtained for both of these differential interferograms. The first interferogram is however marred by atmospheric 'mottling' and residual phase trends. The second interferogram is much cleaner, despite the visually apparent phase changes over regions of high ground. The actual phase change involved (from near black to white) is actually small, it results from errors in baseline estimation, probably caused by large-scale atmospheric refraction effects.

10. Conclusions/Recommendations

These data sets provide good evidence for no substantial or extended subsidence process in the Tombstone region of Arizona.

SAR & InSAR Processing Summary Report — **Tombstone, Arizona: TOM_3 & TOM_4**

1. **Image Acquisition Dates:**	9/1/96, 4/3/97
2. **Temporal Separation:**	1 year 2 months
3. **Processing Stage (1[int], 2[diff] or 3[full]):**	2
4. **DEM details, if used:**	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15m (vertical)
5. **SLC Processing:**	
(i) Scene centre lat/long:	31° 45' 4" N, 109° 45' 33" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. **Ground-range PRI (Amplitude Image) Processing:**	
(i) Scene centre lat/long:	31° 45' 20" N,109° 48' 35" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	97.2km × 107.1km
(iii) Range & Azimuth pixel size:	16m, 16m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. **InSAR Processing**	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	48 m
(b) Derived from Precise State Vectors:	44.0 m
(iii) Altitude of Ambiguity:	214.0 m
(iv) Range × Azimuth extents:	97.4 km × 105.5 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. **Coherence Map Parameters**	
(i) Mean:	23.56
(ii) Standard Deviation:	16.00

9. Analysis/Interpretation of Results

Data Specifications - Interferogram A
ERS acquisitions: 17-Oct-92 and 25-Sep-95
Temporal separation: 2 years 11 months
Perpendicular baseline: 25 m

Data Specifications - Interferogram B
ERS acquisitions: 09-Jan-96 and 04-Mar-97
Temporal separation: 1 year 2 months
Perpendicular baseline: 44 m

Good coherence is obtained for both of these differential interferograms. The first interferogram is however marred by atmospheric 'mottling' and residual phase trends. The second interferogram is much cleaner, despite the visually apparent phase changes over regions of high ground. The actual phase change involved (from near black to white) is actually small, it results from errors in baseline estimation, probably caused by large-scale atmospheric refraction effects.

10. Conclusions/Recommendations

These data sets provide good evidence for no substantial or extended subsidence process in the Tombstone region of Arizona.

Tucson, Arizona **OVERALL RATING: 73%**

1. Marketability *Rating: Good*

Research shows that between 1987 and 1991, the surface of the Tucson Basin dropped 24 mm for every meter drop in the water table. The water table has been falling by about a meter a year since the 1940s. Great interest has been received from the contacts made and it is hoped that a commission for further work may be forthcoming.

2. Subsidence category

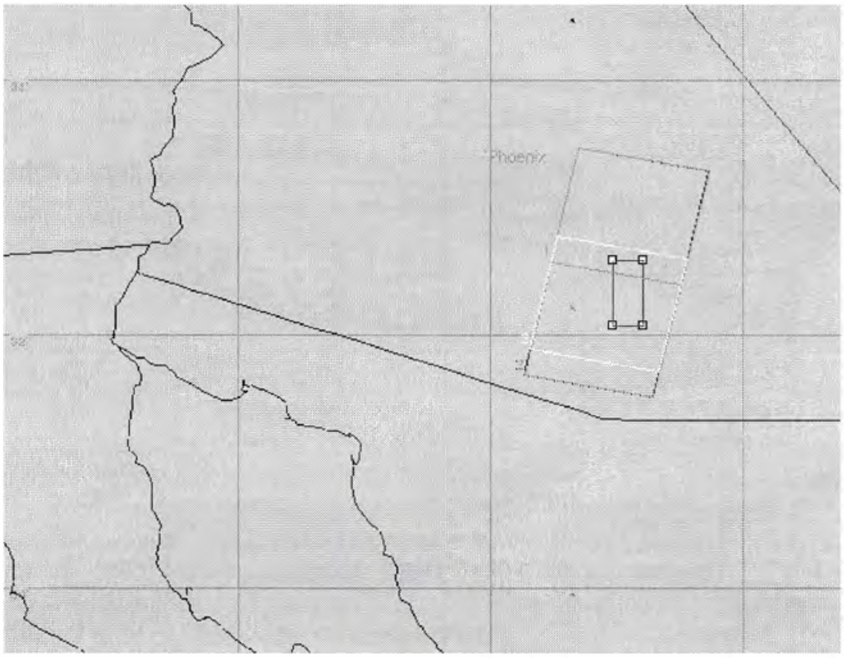
Ground water extraction.

3. Geographical extents and optimal ERS coverage

The extents of the town of Tucson are approximately:

Longitude:	110° 48' W - 111° 3' W	(20 km)
Latitude:	32° 6' N - 32° 19' N	(30 km)

Note: The area defined below has been stretched to enable frame shifting in DESCW.



4. Socio-economic effects of subsidence

Unknown.

5. Customer / contact

Mike Carpenter, Hydrologist, USGS Tucson, AZ. E-mail: mccarp@usgs.gov

Stanley Leake, Research Hydrologist, Tucson, AZ E-mail: saleake@usgs.gov

Donald Pool, Hydrologist, Tucson, AZ E-mail: drpool@usgs.gov

Daniel Evans, Hydrologist, Tucson, AZ E-mail: dwevans@usgs.gov

Maurice Tatlow, Arizona Dept. of Water Resources, Phoenix, AZ 85004
E-mail: matatlow@ADWR.state.az.us

6. Subsidence rate/amount — *Rating: Low*

The Tucson basin is subsiding at an average rate of between half an inch and two inches a year.

7. Ground-truth available — *Rating: Medium*

Extensometer records are available for several locations over the Tucson basin.

8. Land cover — *Rating: Good*

Medium sized urban area surrounded by arid land.

9. ERS Data availability and status — *Rating: Medium*

No suitable ascending pairs available.
Descending: 5 pairs with perpendicular baselines less than 50m and a temporal separation greater than a year.

Receiving station: Prince Albert

10. DEM availability

- USGS 1 arc second resolution xy and 20m z DEM available in 0.5° × 0.5° tiles.
  Cost approx. $100 for first tile, additional tiles much cheaper.
- USGS 3 arc second resolution xy and 20m z DEM for the whole of the US held in-house.
- GTOPO-30 coarse 1km resolution DEM of variable quality held in-house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in-house yet.
- Tandem InSAR.

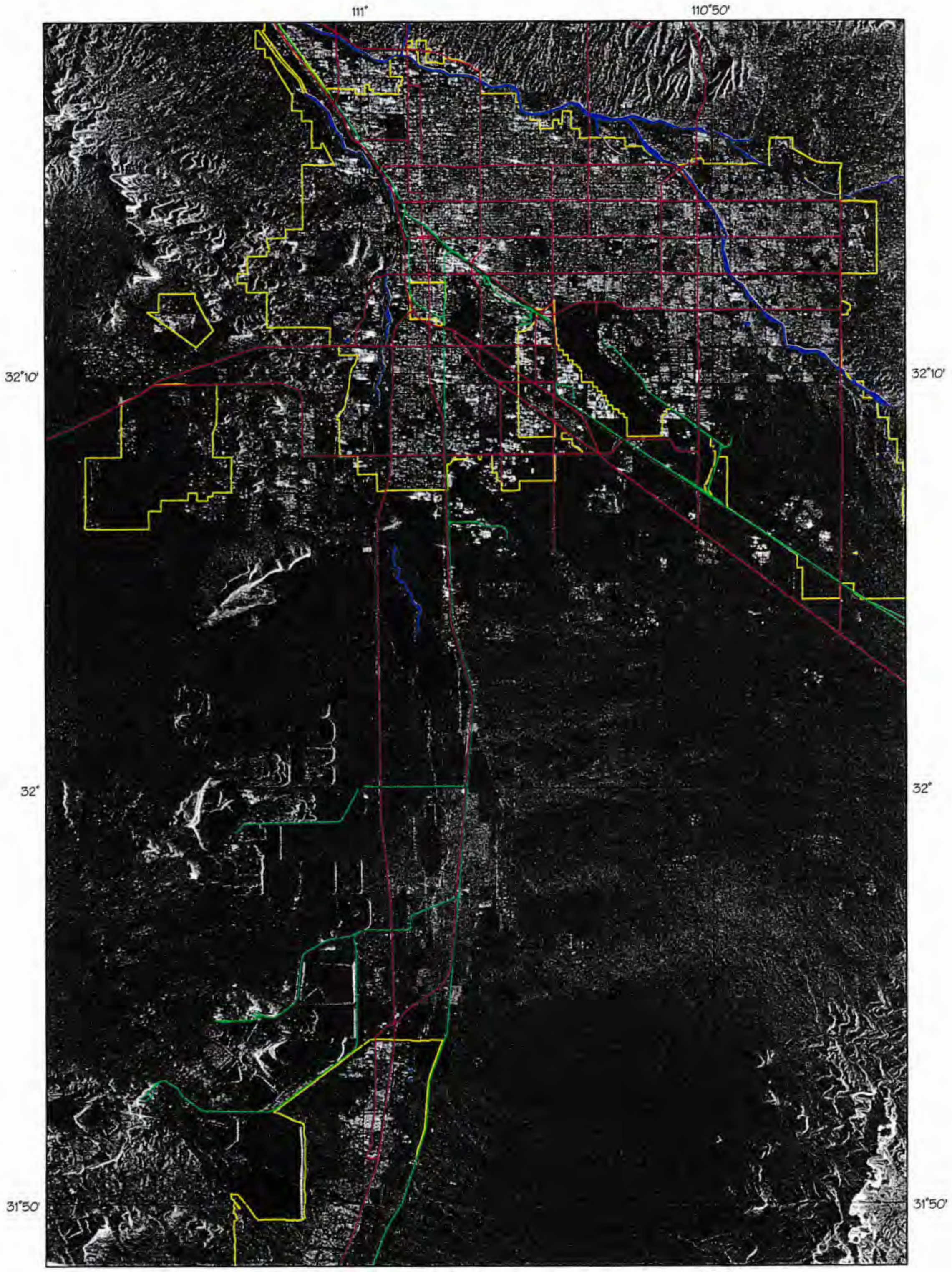
11. Processing status

Two differential interferograms produced.

Radar amplitude image for the Tucson and Green Valley areas

ERS scene date: 7 December 1995

Key:
Yellow: Census/city boundaries
Red: Interstates and main highways
Blue: Water areas
Green: Railroads



0 5 10 15 20 25 km

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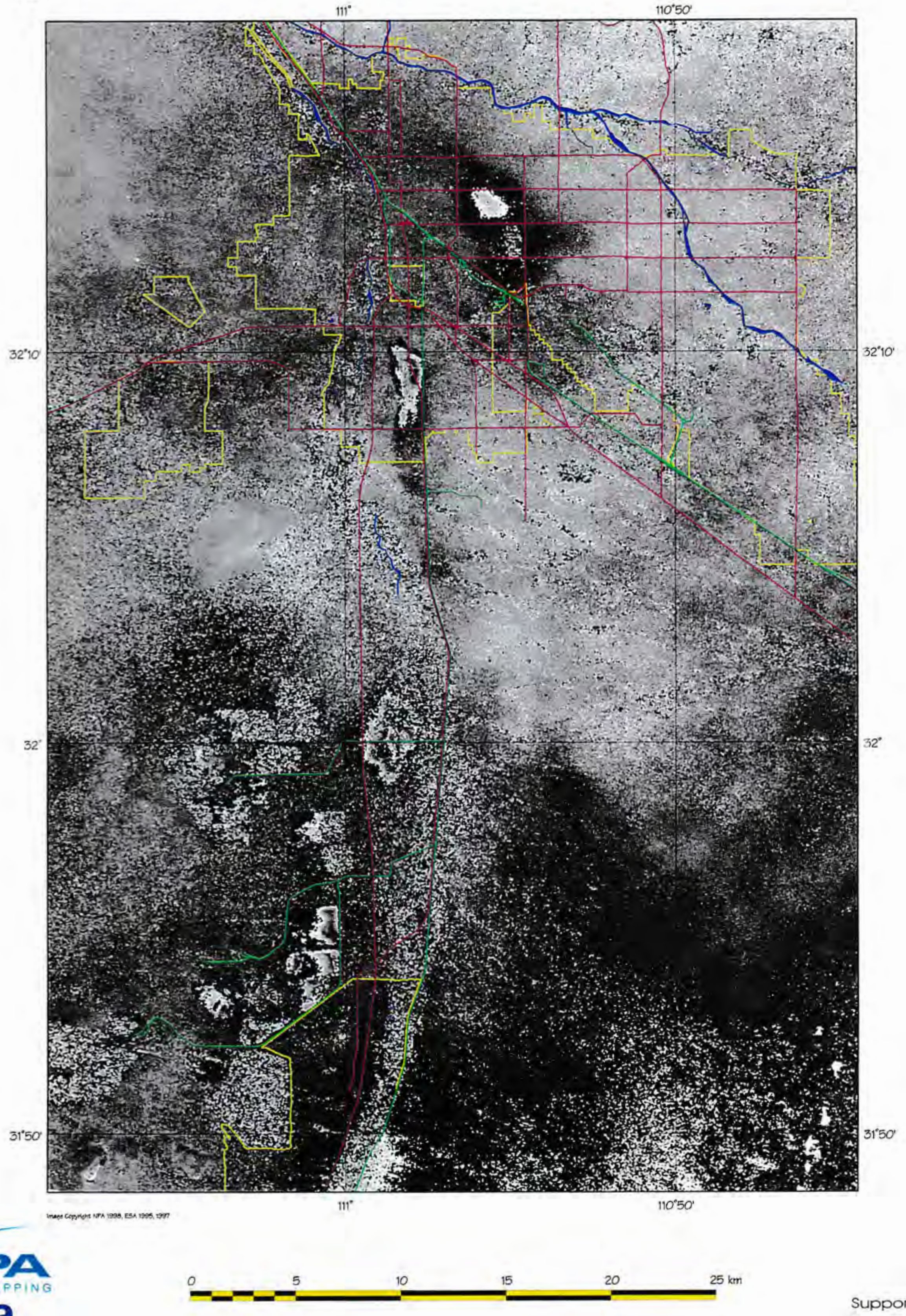
Differential interferogram for the Tucson and Green Valley areas

ERS scene dates: 7 December 1995 & 31 January 1997
Temporal separation: 1 year 1 month
Perpendicular baseline: 0.5 m
Altitude of ambiguity: 18832 m

Key:
Yellow: Census/city boundaries
Red: Interstates and main highways
Blue: Water areas
Green: Railroads



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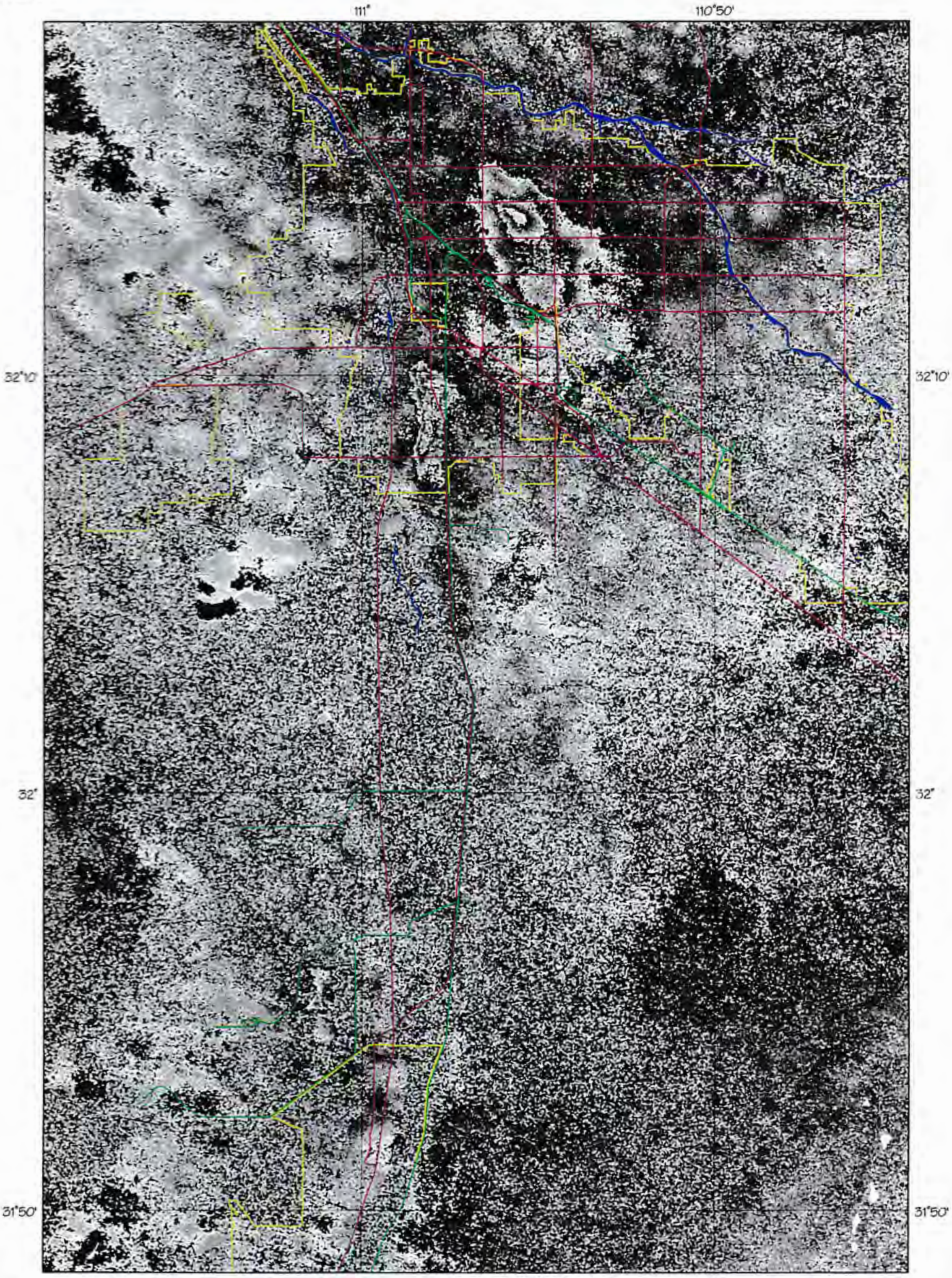
Differential interferogram for the Tucson and Green Valley areas

ERS scene dates: 22 June 1993 & 7 March 1997
Temporal separation: 3 years 9 months
Perpendicular baseline: approx 30 m
Altitude of ambiguity: 313 m

Key:
Yellow: Census/city boundaries
Red: Interstates and main highways
Blue: Water areas
Green: Railroads



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SAR & InSAR Processing Summary Report | **Tucson, Arizona : TUC_1 & TUC_2**

1. Image Acquisition Dates:	7/12/95 , 31/1/97
2. Temporal Separation:	1 year 1 month
3. Processing Stage (1[int], 2[diff] or 3[full]):	3
4. DEM details, if used:	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. SLC Processing:	
(i) Scene centre lat/long:	32° 16' 55" N,111° 04' 09" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.3 km × 106.7 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	32° 16' 41" N,111° 4' 8" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.3 km × 105.6 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	2 m
(b) Derived from Precise State Vectors:	0.5 m
(iii) Altitude of Ambiguity:	18832 m
(iv) Range × Azimuth extents:	100.3 km × 105.5 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	3, 12
8. Coherence Map Parameters	
(i) Mean:	29.85
(ii) Standard Deviation:	15.44

9. Analysis/Interpretation of Results

The spatial separation between the repeat orbital passes (the 'baseline') is insignificant for the one-year acquisitions and small (approx. 30 metres) for the four-year acquisitions. The SAR data has been corrected for the effects of topography using a 100m digital elevation model, and the geo-referencing given by the lat/long grid is accurate to approx. 100m.

The interferometric analysis reveals a pattern of significant and continuing subsidence on a centimetric scale over two extended regions to the South of the Tucson metropolitan area, and some clear surface movement towards and in the mining areas 20-30 km South of Tucson.

Figure 1 (one year separation, zero baseline) is a presentation of the interferometric phase difference between acquisitions. The two metropolitan subsidence regions stand out clearly, with subsidence of order 1.7 cm and 2.5 cm respectively. A further region of subsidence can be identified approx. 15 km directly South of the second metropolitan subsidence area, also with around 2.5 cm of subsidence. Some surface movement phase signature, of order 2cm, can also be identified on the mining regions 10 km further south and slightly west. These latter phase signatures are in the opposite sense to the subsidence activity, that is, if interpreted as vertical movement; they would represent a swelling of the ground surface. It is more likely that these signatures are associated with a slight lateral slip of the surface towards the satellite.

Figure 2 (4-year separation, 30 m baseline) should be contrasted with figure 1. The overall coherence between the data sets is reduced as a consequence of the extended temporal separation, but remaining good over the urban and rocky areas. The urban subsidence remains evident with the two regions now exhibiting of order 6 and 9 cm of displacement. In combination with the one-year separation, this suggests continuing subsidence activity at around 1.5 and 2cm per year for the regions respectively. The coherence South of Tucson is too poor to observe the other surface displacement activity identifiable on figure 1.

10. Conclusions/Recommendations

We would recommend an analysis of a number of further interferometric ERS acquisitions of the region to quantify the surface displacement activity and rates more precisely.

SAR & InSAR Processing Summary Report **Tucson, Arizona : TUC_3 & TUC_4**

1. Image Acquisition Dates:	22/6/93, 7/3/97
2. Temporal Separation:	3 years 9 months
3. Processing Stage (1[int], 2[diff] or 3[full]):	3
4. DEM details, if used:	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. SLC Processing:	
(i) Scene centre lat/long:	32° 16' 16" N, 111° 04' 12"W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.3 km × 106.7 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.3 km × 105.6 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	1 m
(b) Derived from Precise State Vectors:	30 m
(iii) Altitude of Ambiguity:	313 m
(iv) Range × Azimuth extents:	100.4 km × 107.5 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	17.14
(ii) Standard Deviation:	11.17

9. Analysis/Interpretation of Results

The spatial separation between the repeat orbital passes (the 'baseline') is insignificant for the one-year acquisitions and small (approx. 30 metres) for the four-year acquisitions. The SAR data has been corrected for the effects of topography using a 100m digital elevation model, and the geo-referencing given by the lat/long grid is accurate to approx. 100m.

The interferometric analysis reveals a pattern of significant and continuing subsidence on a centimetric scale over two extended regions to the South of the Tucson metropolitan area, and some clear surface movement towards and in the mining areas 20-30 km South of Tucson.

Figure 1 (one year separation, zero baseline) is a presentation of the interferometric phase difference between acquisitions. The two metropolitan subsidence regions stand out clearly, with subsidence of order 1.7 cm and 2.5 cm respectively. A further region of subsidence can be identified approx. 15 km directly South of the second metropolitan subsidence area, also with around 2.5 cm of subsidence. Some surface movement phase signature, of order 2cm, can also be identified on the mining regions 10 km further south and slightly west. These latter phase signatures are in the opposite sense to the subsidence activity, that is, if interpreted as vertical movement; they would represent a swelling of the ground surface. It is more likely that these signatures are associated with a slight lateral slip of the surface towards the satellite.

Figure 2 (4-year separation, 30 m baseline) should be contrasted with figure 1. The overall coherence between the data sets is reduced as a consequence of the extended temporal separation, but remaining good over the urban and rocky areas. The urban subsidence remains evident with the two regions now exhibiting of order 6 and 9 cm of displacement. In combination with the one-year separation, this suggests continuing subsidence activity at around 1.5 and 2cm per year for the regions respectively. The coherence South of Tucson is too poor to observe the other surface displacement activity identifiable on figure 1.

10. Conclusions/Recommendations

We would recommend an analysis of a number of further interferometric ERS acquisitions of the region to quantify the surface displacement activity and rates more precisely.

Davis, California — OVERALL RATING: 53%

1. Marketability — *Rating: Medium*

Randy Hanson, a researcher in the field of subsidence monitoring for 15 years, has expressed great interest in the study.

2. Subsidence category

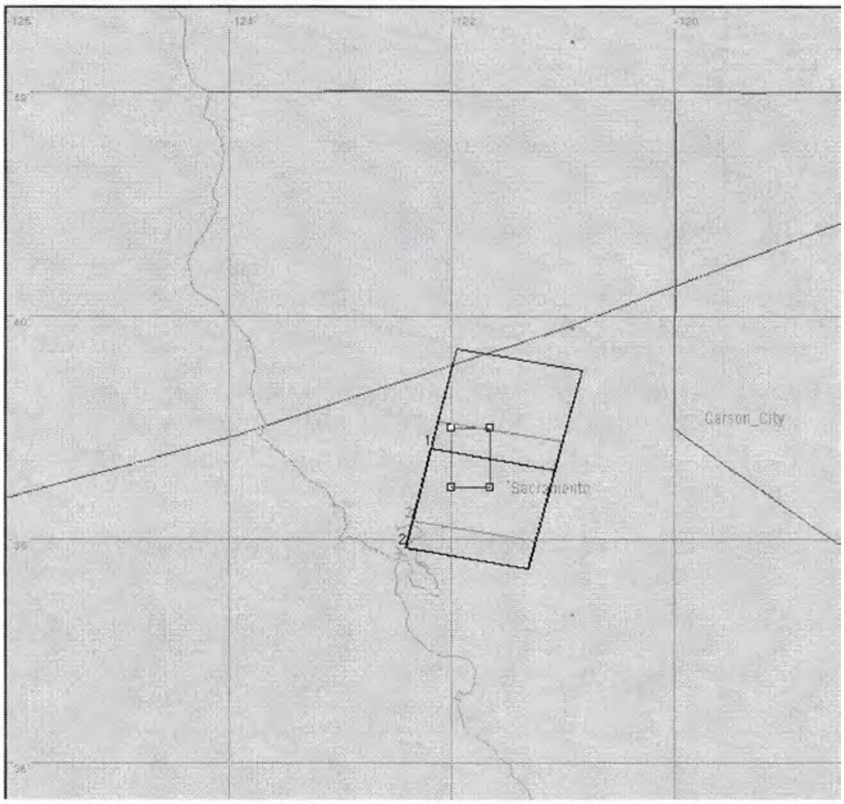
Groundwater abstraction.

3. Geographical extents and optimal ERS coverage

The extents of the Davis area are approximately:

Longitude:	121° 39' W - 122° 0' W	(20 km)
Latitude:	38° 28' N - 38° 39' N	(15 km)

Note: The area defined below has been stretched to enable frame shifting in DESCW.



4. Socio-economic effects of subsidence

Unknown.

5. Customer / contact

Randy Hanson, Hydrologist, U.S. Geological Survey, San Diego, California,
E-mail: rthanson@usgs.gov

6. Subsidence rate/amount *Rating: Low*

Unknown.

7. Ground-truth available *Rating: Poor*

None currently available.

8. Land cover *Rating: Medium*

Large urban area, surrounding land is agricultural.

9. ERS data availability and status *Rating: Medium*

No suitable ascending pairs.

Descending: 14 pairs with perpendicular baselines less than 50m and a temporal separation greater than a year.

Receiving Station: Prince Albert

10. DEM availability

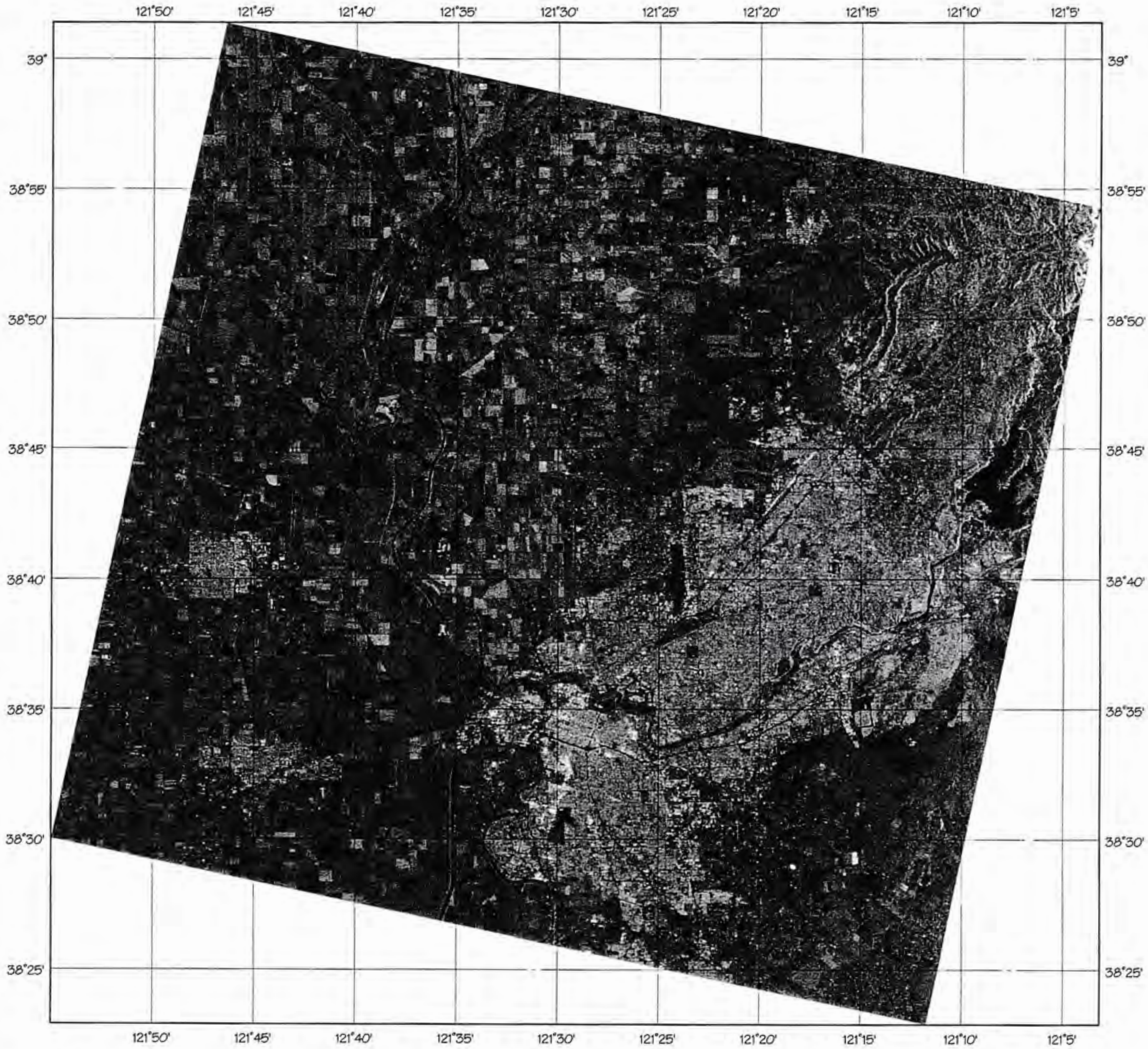
- USGS 1 arc second resolution xy and 20m z DEM available in 0.5° × 0.5° tiles.
  Cost approx. $100 for first tile, additional tiles much cheaper.
- USGS 3 arc second resolution xy and 20m z DEM for the whole of the US held in-house.
- GTOPO-30 coarse 1km resolution DEM of variable quality held in-house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in-house yet.
- Tandem InSAR.

11. Processing status

Differential interferogram produced.

Radar amplitude image for the Davis, California area

ERS scene date: 6 October 1995



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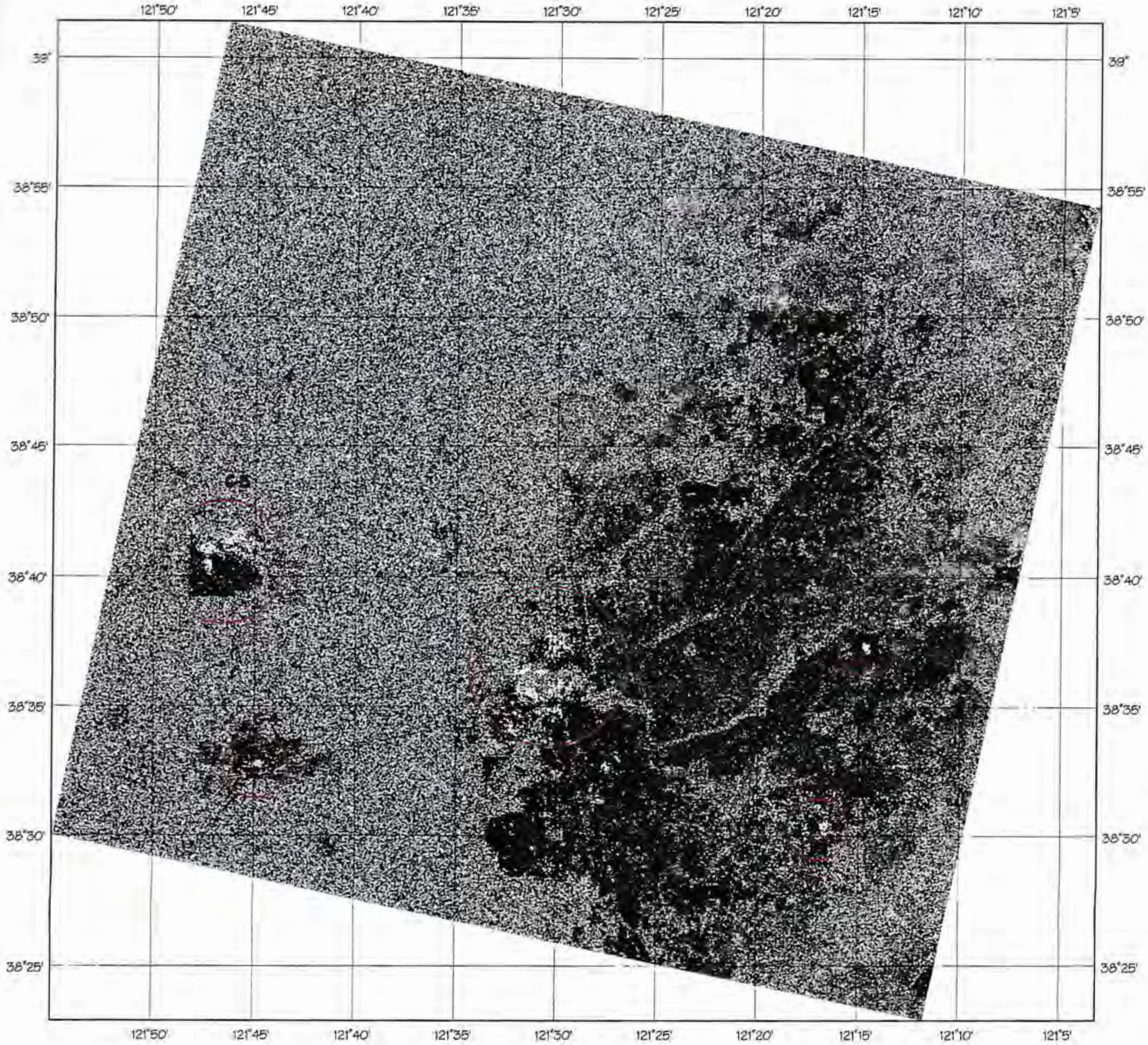
Differential interferogram for the Davis, California area

ERS scene dates: 6 October 1995 & 11 October 1997
Temporal separation: 2 years
Perpendicular baseline: 25.3 m
Altitude of ambiguity: 372.2 m

Rings indicate fringe features in this image



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SAR & InSAR Processing Summary Report **Davis, California: DAV_1 & DAV_2**

1. **Image Acquisition Dates:**	6/10/95, 11/10/97
2. **Temporal Separation:**	2 years
3. **Processing Stage (1[int], 2[diff] or 3[full]):**	2
4. **DEM details, if used:**	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. **SLC Processing:**	
(i) Scene centre lat/long:	38° 31' 34"N, 121° 43' 9"W
(ii) Full- (or sub-) scene Range × Azimuth extents:	99.3 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. **Ground-range PRI (Amplitude Image) Processing:**	
(i) Scene centre lat/long:	38° 31' 44" N,121° 45' 48" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	107.0 km × 98.2 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. **InSAR Processing**	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	26 m
(b) Derived from Precise State Vectors:	25.3 m
(iii) Altitude of Ambiguity:	372.2 m
(iv) Range × Azimuth extents:	98.2 km × 107.0 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. **Coherence Map Parameters**	
(i) Mean:	14.94
(ii) Standard Deviation:	11.36

9. Analysis/Interpretation of Results

The region surrounding Davis is cultivated, and good coherence is only observed over the metropolitan area and the mountains to the West of the full scene. Overall the quality of the data is good, with no significant atmospheric artefacts, although there is some phase variation across the scene, of order half a phase cycle.

10. Conclusions/Recommendations

There are no extended subsidence features on the differential interferogram. There is a suggestion of slight (1 cm) subsidence in five localised regions. A repeat acquisition, preferably with a longer temporal separation, is needed to confirm subsidence in these areas.

Category	Label	Co-ordinates	Comments
5 class C features	C1	121° 30' W 38° 37' N	Probable localised subsidence <0.5 cm/year
	C2	121° 14' 30" W 38° 37' N	Probable localised subsidence <0.5 cm/year
	C3	121° 17' W 38° 30' N	Probable localised subsidence <0.5 cm/year
	C4	121° 45' W 38° 33' N	Probable localised subsidence <0.5 cm/year
	C5	121° 44' W 38° 40' N	Probable localised subsidence <0.5 cm/year

Categories: **A** *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/ Feature of interest*

Lancaster, California **OVERALL RATING: 67%**

1. Marketability *Rating: Medium*

Land subsidence in the Lancaster area was first reported in the 1950's, and by 1967 as much as 2 feet of subsidence had been experienced over an area of about 200 mi^2. As well as the town of Lancaster subsidence has affected the Edwards Air Force Base and surrounding areas.

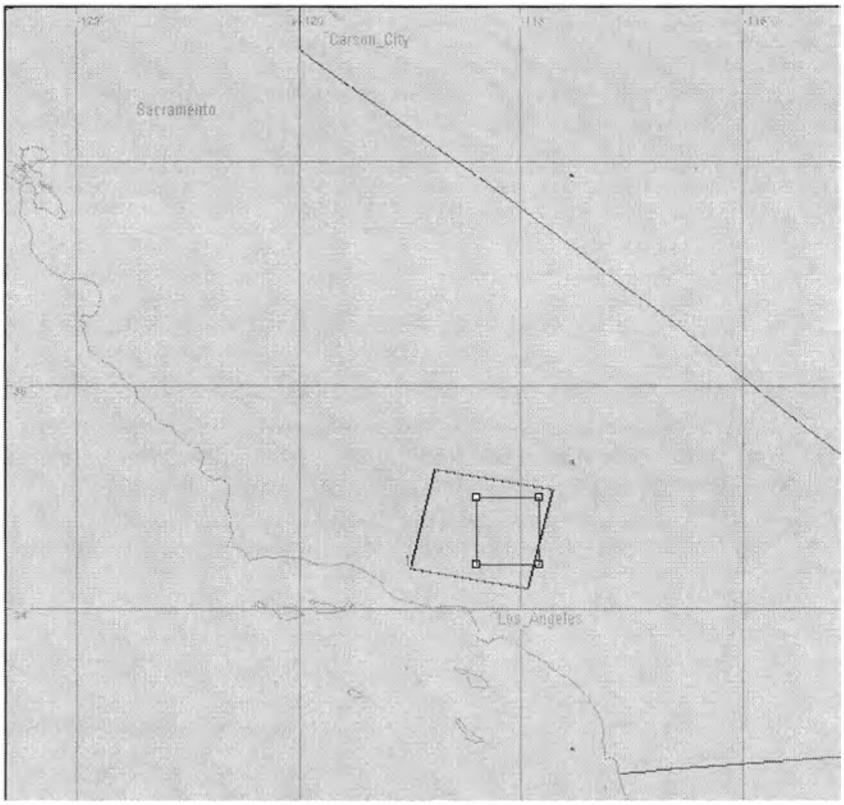
2. Subsidence category

Groundwater withdrawal.

3. Geographical extents and optimal ERS coverage

The extents of the Lancaster area are approximately:

Longitude:	117° 50' W - 118° 24' W	(40 km)
Latitude:	34° 24' N - 35° 0' N	(30 km)



4. Socio-economic effects of subsidence

The subsidence has caused earth fissures and cracks on the ground surface and these have adversely affected the use of the Rogers Lake bed as a runway for both aeroplanes and space shuttles.

5. Customer / contact

Marti Ikehara, U.S. Geological Survey, Sacramento, California, E-mail: mikehara@usgs.gov

Devin Galloway U.S. Geological Survey, Sacramento, California, E-mail: dlgallow@usgs.gov

6. Subsidence rate/amount — *Rating: Low*

Current rate of subsidence unknown, but between about 1930 and 1992 an estimated maximum of 6 feet of subsidence is thought to have occurred.

7. Ground-truth available — *Rating: Poor*

None currently available.

8. Land cover — *Rating: Good*

Lancaster is situated in the Mojave Desert and therefore vegetation cover is at a minimum.

9. ERS data availability and status — *Rating: High*

No suitable ascending pairs.

Descending: 44 pairs with perpendicular baselines less than 50m and a temporal separation greater than a year.

Receiving Station: Prince Albert

10. DEM availability

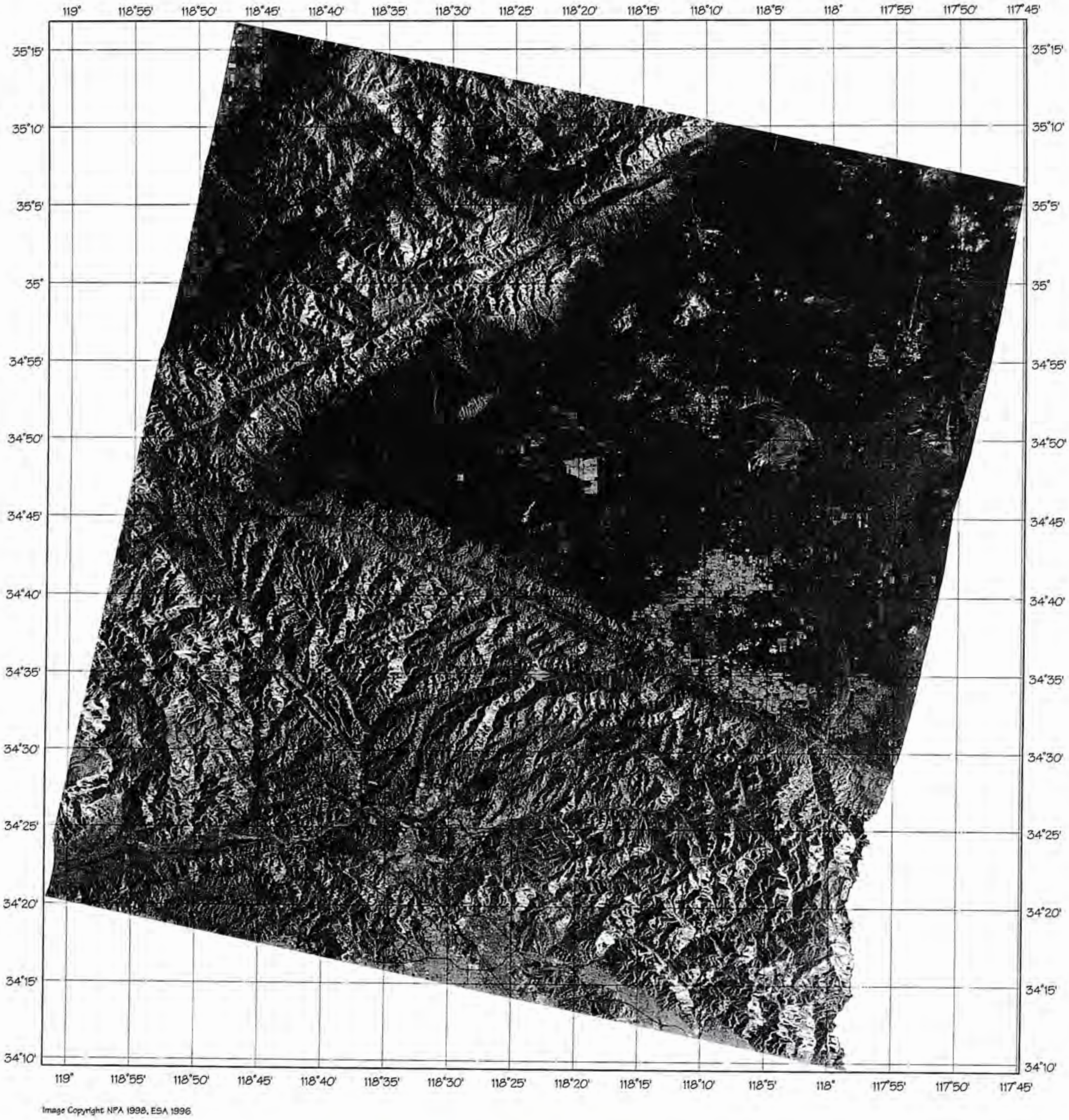
- USGS 1 arc second resolution xy and 20m z DEM available in 0.5° × 0.5° tiles.
  Cost approx. $100 for first tile, additional tiles much cheaper.
- USGS 3 arc second resolution xy and 20m z DEM for the whole of the US held in-house.
- GTOPO-30 coarse 1km resolution DEM of variable quality held in-house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in-house yet.
- Tandem InSAR.

11. Processing status

Two differential interferograms produced.

Radar amplitude image for the Lancaster, California area

ERS scene date: 11 January 1996



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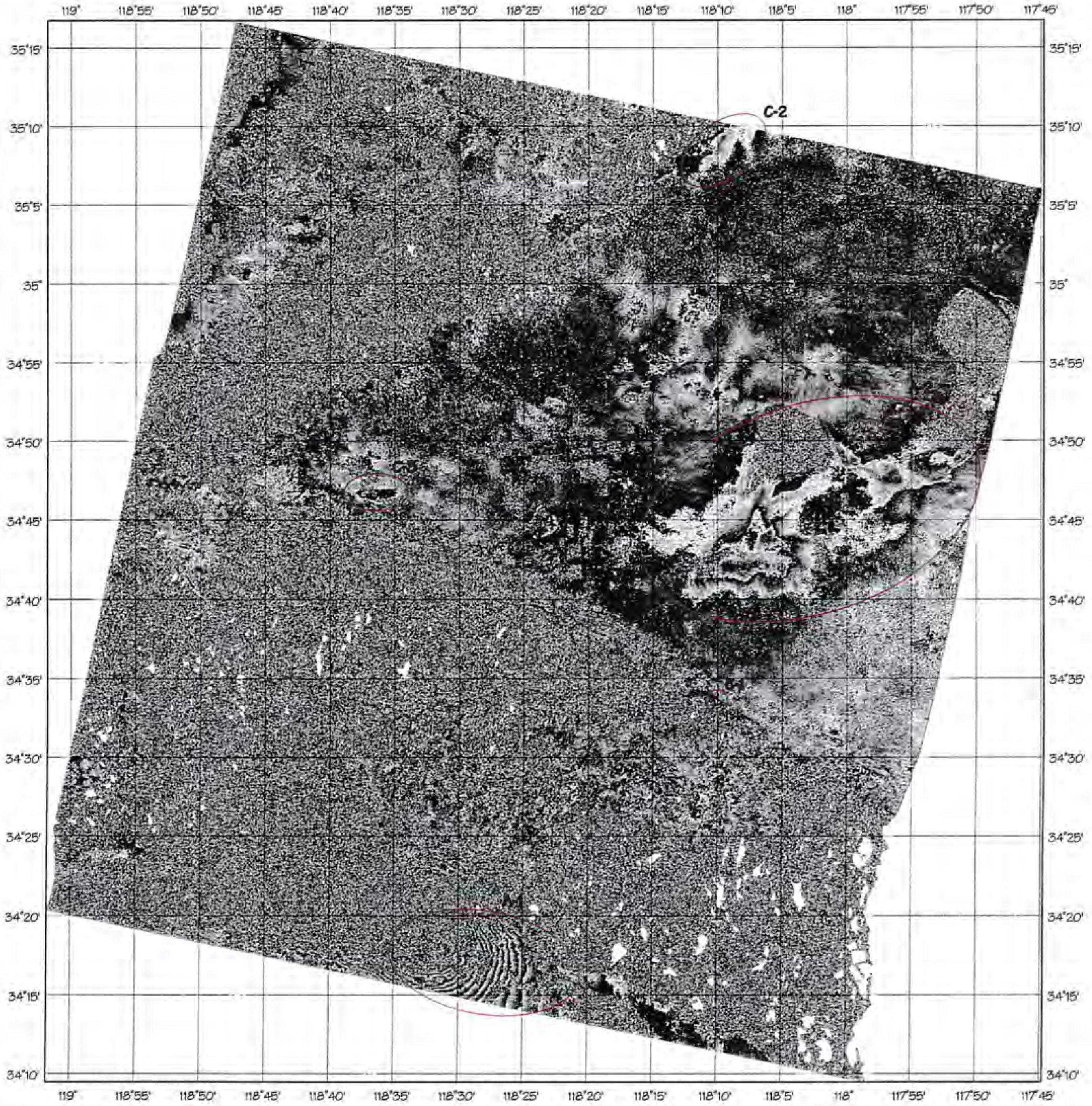
Differential interferogram for the Lancaster, California area

ERS scene dates: 23 November 1992 & 6 December 1995
Temporal separation: 3 years 1 month
Perpendicular baseline: 122.8 m
Altitude of ambiguity: 76.7 m

Rings indicate fringe features in this image



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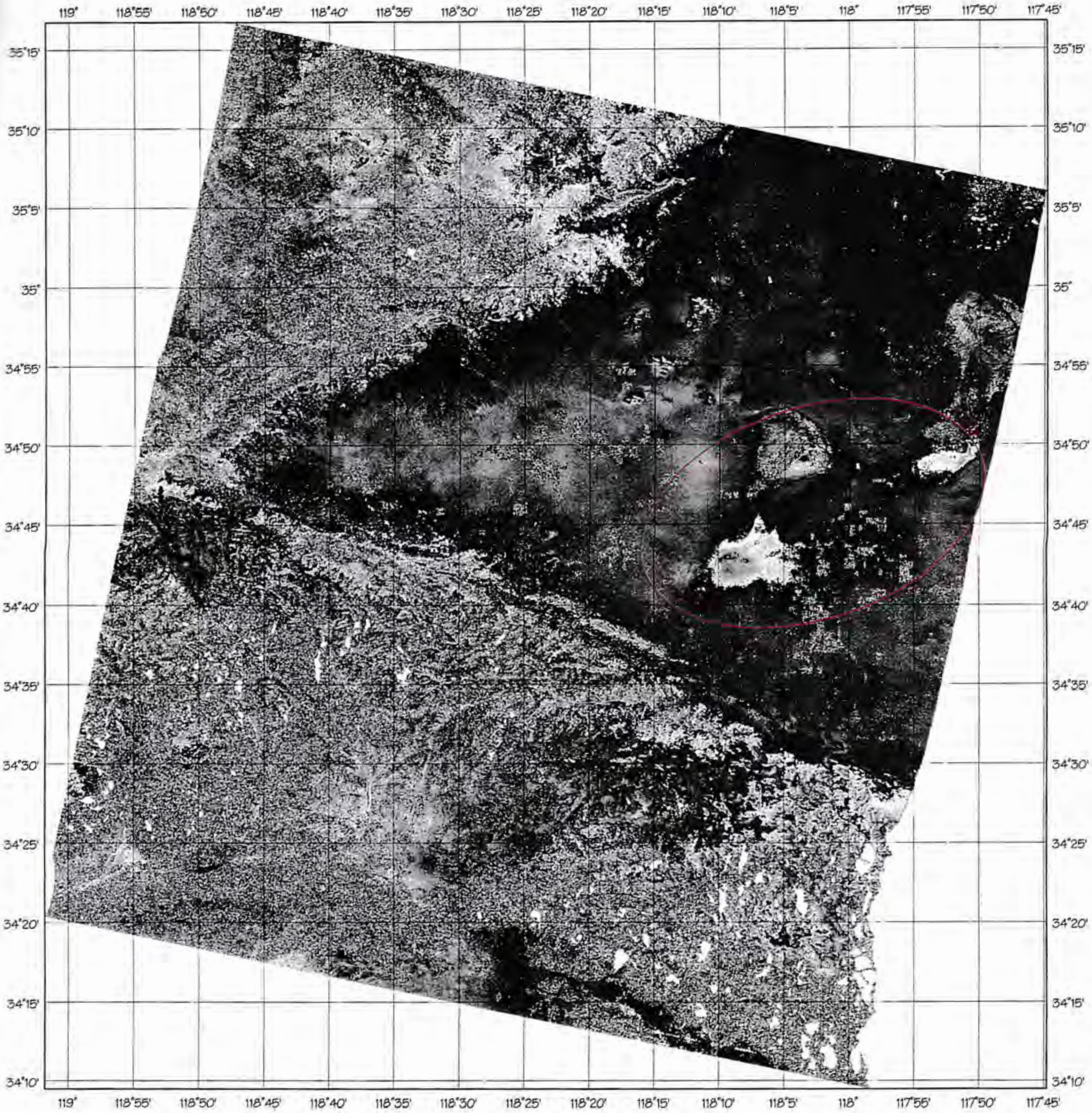
Differential interferogram for the Lancaster, California area

ERS scene dates: 11 January 1996 & 6 March 1997
Temporal separation: 1 year 2 months
Perpendicular baseline: 54.3 m
Altitude of ambiguity: 173.4 m

Rings indicate fringe features in this image



0 10 20 30 40 50 km

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SAR & InSAR Processing Summary Report — **Lancaster, California: LAN_1 & LAN_2**

1. Image Acquisition Dates:	23/11/92, 6/12/95
2. Temporal Separation:	3 years 1 month
3. Processing Stage (1[int], 2[diff] or 3[full]):	3
4. DEM details, if used:	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. SLC Processing:	
(i) Scene centre lat/long:	34° 43' 5" N, 118° 22' 19"W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	34° 43' 19" N,118° 25' 32" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	97.0 km × 107.1 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	127 m
(b) Derived from Precise State Vectors:	122.8 m
(iii) Altitude of Ambiguity:	76.7 m
(iv) Range × Azimuth extents:	97.4 km × 106.9 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	17.36
(ii) Standard Deviation:	13.07

9. Analysis/Interpretation of Results

Good coherence is obtained for both of these differential interferograms over the Mojave Desert. The interferograms exhibit no significant atmospheric artefacts over this region.

In the 1-year interferogram the only significant feature of interest is an apparent region of subsidence centred on the town of Lancaster, of a magnitude of around 2 cm, and with a diameter of around 5 km. There is also a second smaller region with a reduced signature some 25 km ENE of Lancaster of a magnitude of around 1 cm.

In the 3-year interferogram the two prominent interferometric features are the Northern half of the uplift field associated with the Northridge earthquake at the Southern edge of the image, and a more extended subsidence field centred around the town of Lancaster, confirming the rate of 2 cm/year observed on the 1-year interferogram. Overall this subsidence field can now be seen to extend roughly 30 km to the East with a width of approximately 15 km.

Some small phase variations are also observed elsewhere within the plain on the 3-year interferogram at a low level (features C1, C2 and C3). The phase variations associated with C1 and C3, if interpreted as subsidence, would correspond to a small uplift of the surface over the acquisition interval.

These interferograms overlap spatially, and for the 3-year interferogram, temporally with the differential interferogram generated over the Los Angeles area (ERS acquisitions 4-Oct-93 and 7-Dec-95). On that interferogram a clear uplift signature was identified at 117° 53' W, 34° 33' N, as well as a region of general phase variation just North of the San Andreas Fault. The corresponding spatial region on these interferograms is however completely stable. The most likely explanation is that the phase variations observed on the Los Angeles interferogram were due to unusually clear and localised atmospheric effects - emphasising the importance of making repeat differential analyses to eliminate atmospheric perturbations.

10. Conclusions/Recommendations

Category	Label	Co-ordinates	Comments
2 class A features	A1	118° 37' W 34° 17' N	Northridge earthquake
	A2	118° 07' W 34° 42' N	Extended region of subsidence of approx. 2 cm/year centred on Lancaster.
3 class C features	C1	118° 10' W 34° 33' N	Low level phase variations
	C2	118° 10' W 35° 08' N	Low level phase variations
	C3	118° 35' W 34° 47' N	Low level phase variations

Categories: A *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/Feature of interest*

SAR & InSAR Processing Summary Report **Lancaster, California: LAN_3 & LAN_4**

1. Image Acquisition Dates:	11/1/96, 6/3/97
2. Temporal Separation:	1 year 2 months
3. Processing Stage (1[int], 2[diff] or 3[full]):	3
4. DEM details, if used:	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. SLC Processing:	
(i) Scene centre lat/long:	34° 43' 9" N, 118° 22' 16" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	99.3 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	34° 43' 25" N,118° 25' 26" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	97.0 km × 107.1 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	55 m
(b) Derived from Precise State Vectors:	54.3 m
(iii) Altitude of Ambiguity:	173.4 m
(iv) Range × Azimuth extents:	97.3 km × 106.9 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	24.83
(ii) Standard Deviation:	17.88

9. Analysis/Interpretation of Results

Good coherence is obtained for both of these differential interferograms over the Mojave Desert. The interferograms exhibit no significant atmospheric artefacts over this region.

In the 1-year interferogram the only significant feature of interest is an apparent region of subsidence centred on the town of Lancaster, of a magnitude of around 2 cm, and with a diameter of around 5 km. There is also a second smaller region with a reduced signature some 25 km ENE of Lancaster of a magnitude of around 1 cm.

In the 3-year interferogram the two prominent interferometric features are the Northern half of the uplift field associated with the Northridge earthquake at the Southern edge of the image, and a more extended subsidence field centred around the town of Lancaster, confirming the rate of 2 cm/year observed on the 1-year interferogram. Overall this subsidence field can now be seen to extend roughly 30 km to the East with a width of approximately 15 km.

Some small phase variations are also observed elsewhere within the plain on the 3-year interferogram at a low level (features C1, C2 and C3). The phase variations associated with C1 and C3, if interpreted as subsidence, would correspond to a small uplift of the surface over the acquisition interval.

These interferograms overlap spatially, and for the 3-year interferogram, temporally with the differential interferogram generated over the Los Angeles area (ERS acquisitions 4-Oct-93 and 7-Dec-95). On that interferogram a clear uplift signature was identified at 117° 53' W, 34° 33' N, as well as a region of general phase variation just North of the San Andreas Fault. The corresponding spatial region on these interferograms is however completely stable. The most likely explanation is that the phase variations observed on the Los Angeles interferogram were due to unusually clear and localised atmospheric effects - emphasising the importance of making repeat differential analyses to eliminate atmospheric perturbations.

10. Conclusions/Recommendations

Category	Label	Co-ordinates	Comments
2 class A features	A1	118° 37' W 34° 17' N	Northridge earthquake
	A2	118° 07' W 34° 42' N	Extended region of subsidence of approx. 2 cm/year centred on Lancaster.
3 class C features	C1	118° 10' W 34° 33' N	Low level phase variations
	C2	118° 10' W 35° 08' N	Low level phase variations
	C3	118° 35' W 34° 47' N	Low level phase variations

Categories: A *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/Feature of interest*

Los Angeles, California OVERALL RATING: 73%

1. Marketability *Rating: Medium*

The Hollywood district of Los Angeles is the location of reported subsidence due to Metro construction. Long Beach is subject to the greatest recorded oilfield subsidence, with a subsidence bowl 9m deep.

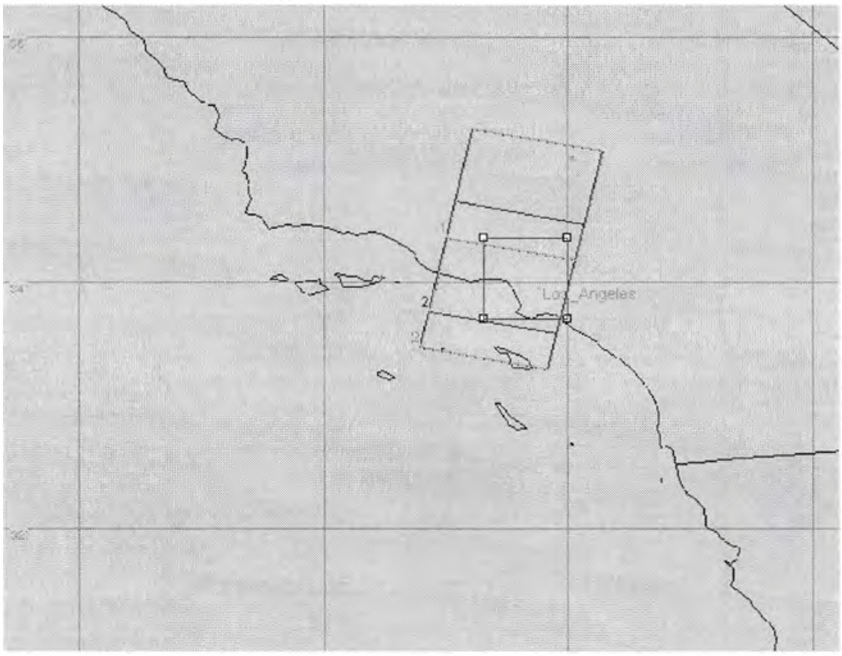
2. Subsidence category

Subsidence due to Metro Construction and groundwater extraction in the Los Angeles area. Also subsidence related to oil extraction from the Torrance and Wilmington oil fields, south Los Angeles (Redondo Beach to Long Beach).

3. Geographical extents and optimal ERS coverage

The extents of the Los Angeles area are approximately:

Longitude:	118° 0' W - 118° 41' W	(50 km)
Latitude:	33° 42' N - 34° 21' N	(70 km)



4. Socio-economic effects of subsidence

The cumulative costs from subsidence in Long Beach are more than $100 million.
In Hollywood a number of claims have been made for damage to buildings. Also Hollywood Boulevard itself has been damaged by the Metro construction.

5. Customer / contact

Don Helm, Nevada Bureau of Mines and Geology, University of Nevada-Reno,
E-mail: helm@eng.morgan.edu

Greg Stanley, University of Texas, E-mail: gstanley@pe.utexas.edu

6. Subsidence rate/amount *Rating: Medium*

Subsidence amounts due to Metro construction reported to be 1 to 25 cm over an area several kilometres in length and fifty metres in width.
Subsidence rates of 3 cm/year at Redondo Beach and Long Beach due to oil extraction.

7. Ground-truth available *Rating: Poor*

Levelling surveys conducted along several routes in 1994.

8. Land cover *Rating: Good*

Major urban area.

9. ERS data availability and status *Rating: High*

No suitable ascending pairs.
Descending: 28 pairs with perpendicular baselines less than 50m and a temporal separation greater than a year.

Receiving Station: Prince Albert

10. DEM availability

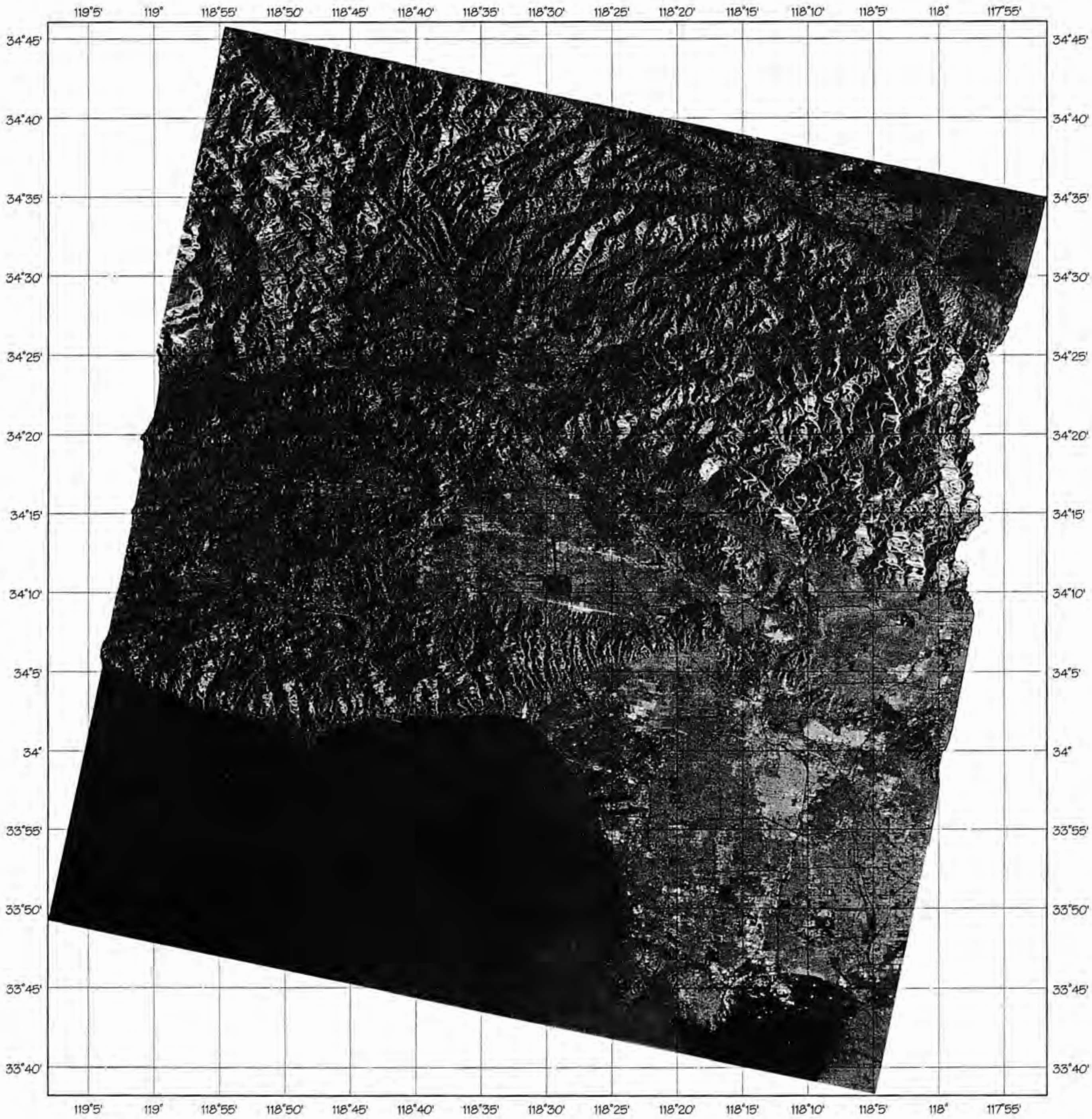
- USGS 1 arc second resolution xy and 20m z DEM available in 0.5° × 0.5° tiles.
  Cost approx. $100 for first tile, additional tiles much cheaper.
- USGS 3 arc second resolution xy and 20m z DEM for the whole of the US held in-house.
- GTOPO-30 coarse 1km resolution DEM of variable quality held in-house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in-house yet.
- Tandem InSAR.

11. Processing status

Differential interferogram produced.

Radar amplitude image for the Los Angeles area

ERS-1 scene date: 4 October 1993



0 10 20 30 40 50 km

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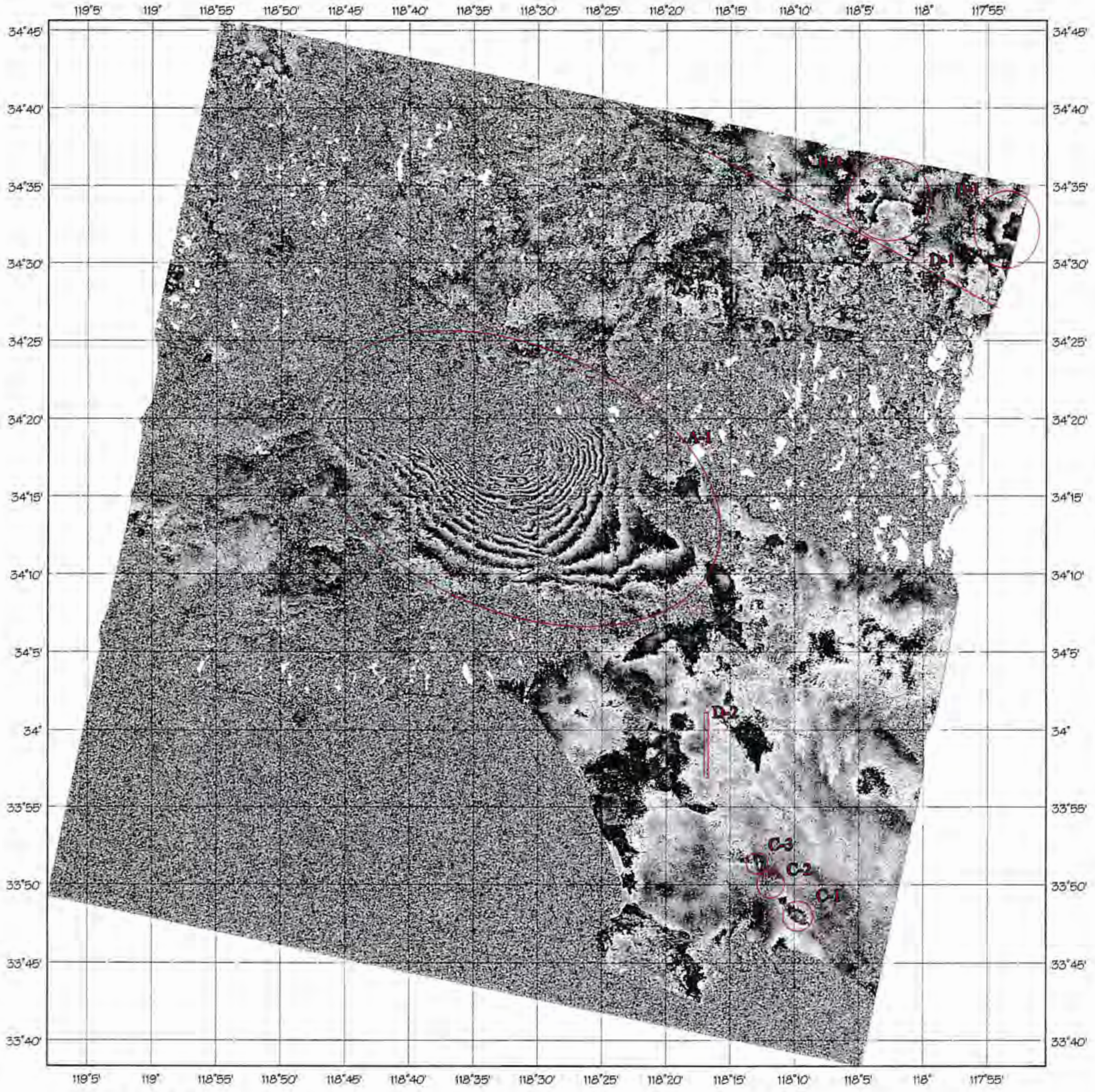
Differential interferogram for the Los Angeles area

ERS scene dates: 4 October 1993 & 7 December 1995
Temporal separation: 2 years 2 months
Perpendicular baseline: 67.76 m
Altitude of ambiguity: 139.29 m

Rings indicate fringe features in this image



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SAR & InSAR Processing Summary Report | **Los Angeles: LOS_1 & LOS_2**

1. Image Acquisition Dates:	4/10/93 7/12/95
2. Temporal Separation:	2 years 2 months
3. Processing Stage (1[int], 2[diff] or 3[full]):	3
4. DEM details, if used:	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. SLC Processing:	
(i) Scene centre lat/long:	34° 12’ 04” N,118° 29’ 10”W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	34° 12’ 17” N,118° 32’ 14” W
(ii) Full- (or sub-) scene Range × Azimuth extents:	99.2 km × 107.0 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	55 m
(b) Derived from Precise State Vectors:	67.76 m
(iii) Altitude of Ambiguity:	139.29 m
(iv) Range × Azimuth extents:	99.2 km × 107.0 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	18.60
(ii) Standard Deviation:	14.63

9. Analysis/Interpretation of Results

This differential interferogram was generated using a 100 m resolution DEM.

The after-effects of the Northridge earthquake are the most immediate feature of the interferogram, with over 0.5 metres of surface heave over a region some 30 km in diameter.

The town of Palmdale is in the northeast corner of the scene, just North of the San Andreas Fault. Unambiguous surface displacement can be observed in the town itself, and more clearly to the East, of a magnitude which would correspond to around 4-6 cm of vertical movement over the two-year interval between acquisitions. It is however possible that the phase variations arise from a lateral strain field associated with the fault, as opposed to a vertical displacement. There is no evidence of lateral movement along this section of the San Andreas Fault from this pair of acquisitions.

Small phase variations can be observed in the mountainous region south of the San Andreas Fault. These variations are most probably residual topographic phase artefacts arising from errors in the DEM used for the differential interferometric processing.

The city of Los Angeles in the southeast corner of the image is of interest because there are reports of urban subsidence associated with fluid abstraction and underground tunnelling work. The coherence over the Los Angeles metropolitan area is good. Regrettably the interferogram exhibits a relatively high degree of phase noise associated with atmospheric effects (and possible DEM errors), and the identification of any such effects cannot be made with any degree of confidence. A number of possibly anomalous locations have however been marked on the interferogram. If these are the effect of surface displacement, then it is at a low level of order 1-2 cm. One of the marked areas in the Long Beach area has a phase signature that would correspond to a swelling of the ground surface. Raised freeways in the urban area are evident in the interferometric phase; the elevation of the freeways is not represented by the DEM, and the small phase signatures associated with their height is made visible to the eye because of their linear characteristics.

10. Conclusions/Recommendations

Category	Label	Grid ref.	Comments
1 class A feature	A1	118° 33' E 34° 20' N	Post Northridge earthquake surface heave (0.5 metres)
2 class B features	B1	117° 52' E 34° 32' N	Subsidence, or possibly lateral surface strain effects
	B2	118° 3' E 34° 34' N	Palmdale. Subsidence, or possibly lateral surface strain effects
3 class C features	C1	118° 9' E 33° 48' N	Possible swelling
	C2	118° 12' E 33° 50' N	Possible subsidence
	C3	118° 13' E 33° 52' N	Possible subsidence
2 class D features	D1	118° 17' E 34° 35' N	The San Andreas fault
	D2	LA city	Elevated freeways

Categories: A *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/Feature of interest*

We would recommend that a second data set be acquired to provide a more comprehensive interferometric coverage of Palmdale and the surrounding areas along the San Andreas Fault.

Mendota, California — OVERALL RATING: 53%

1. Marketability — *Rating:* Medium

Mendota is located in the San Joaquin Valley, California, which historically has the world's largest subsidence bowl, 9900 km^2 in extent and reaching 9m deep.

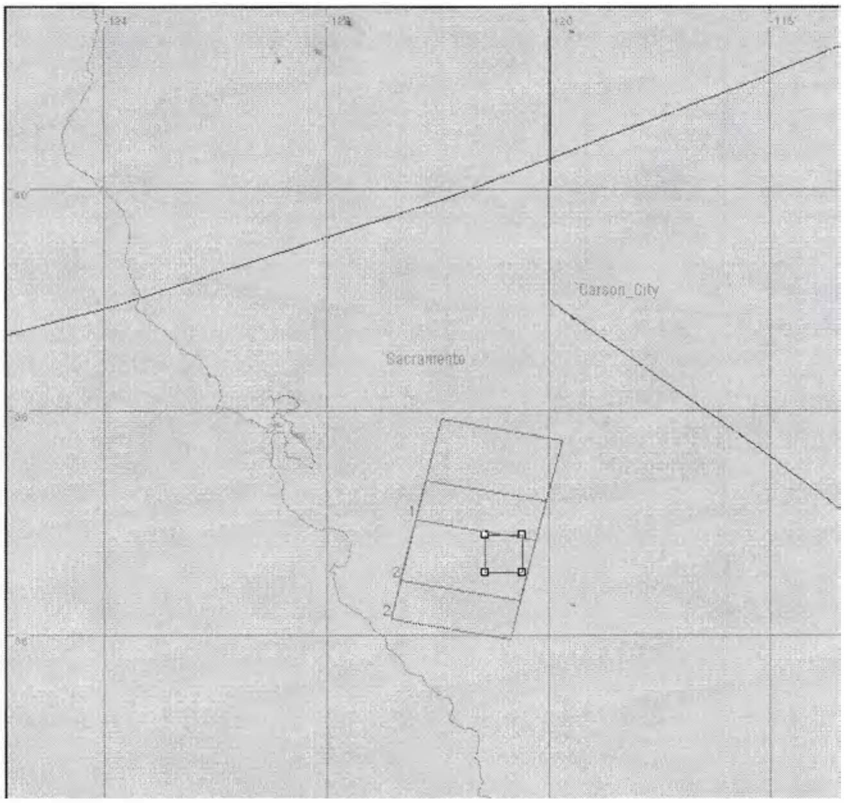
2. Subsidence category

Ground water extraction.

3. Geographical extents and optimal ERS coverage

The extents of the Mendota area are approximately:

Longitude:	120° 14' W - 120° 34' W	(20 km)
Latitude:	36° 34' N - 36° 54' N	(20 km)



4. Socio-economic effects of subsidence

Subsidence damage to wells and irrigation canals in the San Joaquin Valley has cost over $50 million.

5. Customer / contact

Stanley A Leake, Research Hydrologist, Tucson, Email: saleake@usgs.gov

6. Subsidence rate/amount *Rating: Low*

Current rate of subsidence unknown.

7. Ground-truth available *Rating: Poor*

Unknown.

8. Land cover *Rating: Poor*

Small urban area surrounded by agricultural land.

9. ERS data availability and status *Rating: High*

No suitable ascending pairs.

Descending: 12 pairs with perpendicular baselines less than 50m and a temporal separation greater than a year.

Receiving Station: Prince Albert

10. DEM availability

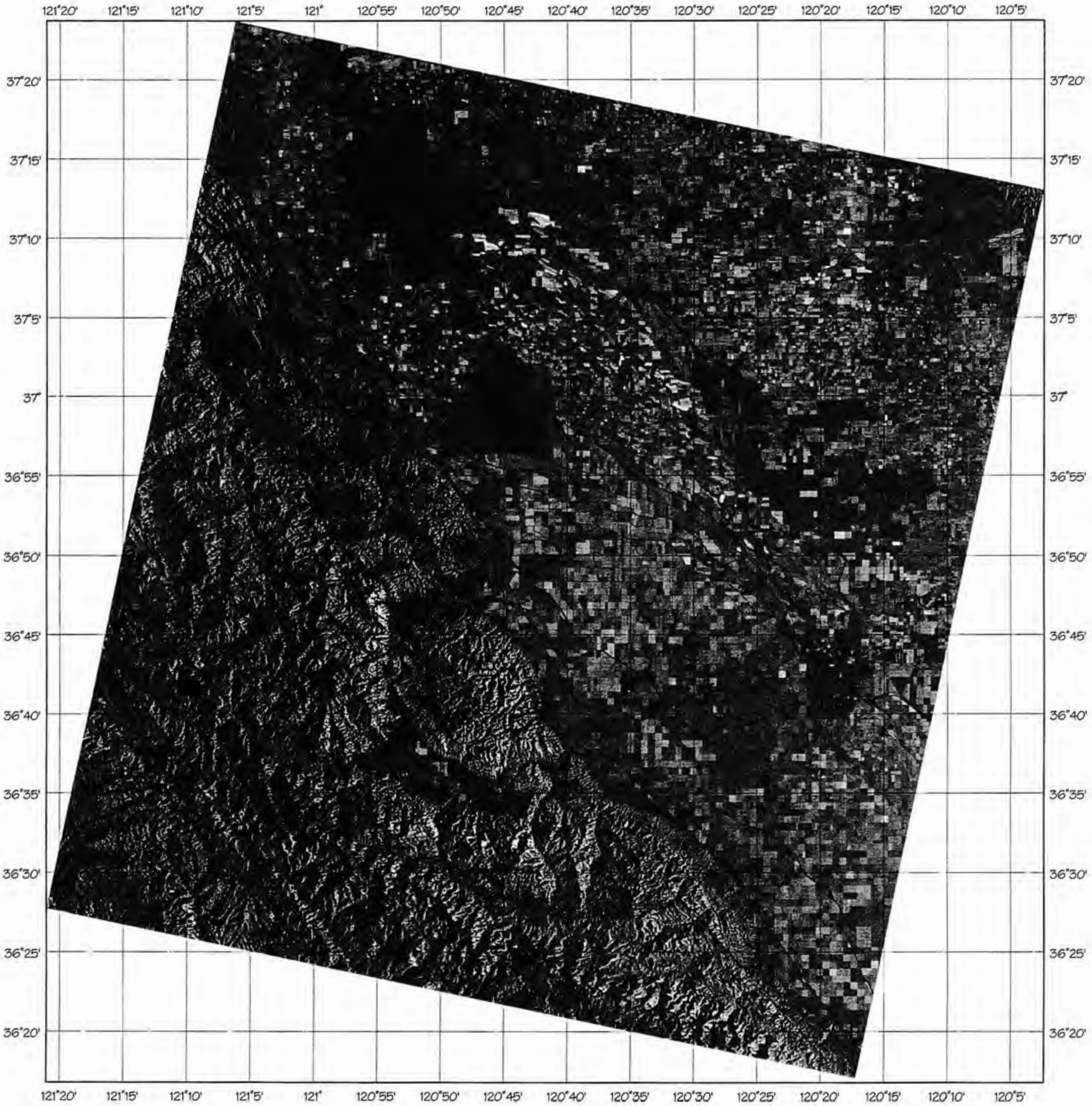
- USGS 1 arc second resolution xy and 20m z DEM available in 0.5° × 0.5° tiles.
  Cost approx. $100 for first tile, additional tiles much cheaper.
- USGS 3 arc second resolution xy and 20m z DEM for the whole of the US held in-house.
- GTOPO-30 coarse 1km resolution DEM of variable quality held in-house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in-house yet.
- Tandem InSAR.

11. Processing status

Differential interferogram produced.

Radar amplitude image for the Mendota, California area

ERS scene date: 3 January 1993



0 10 20 30 40 50 km

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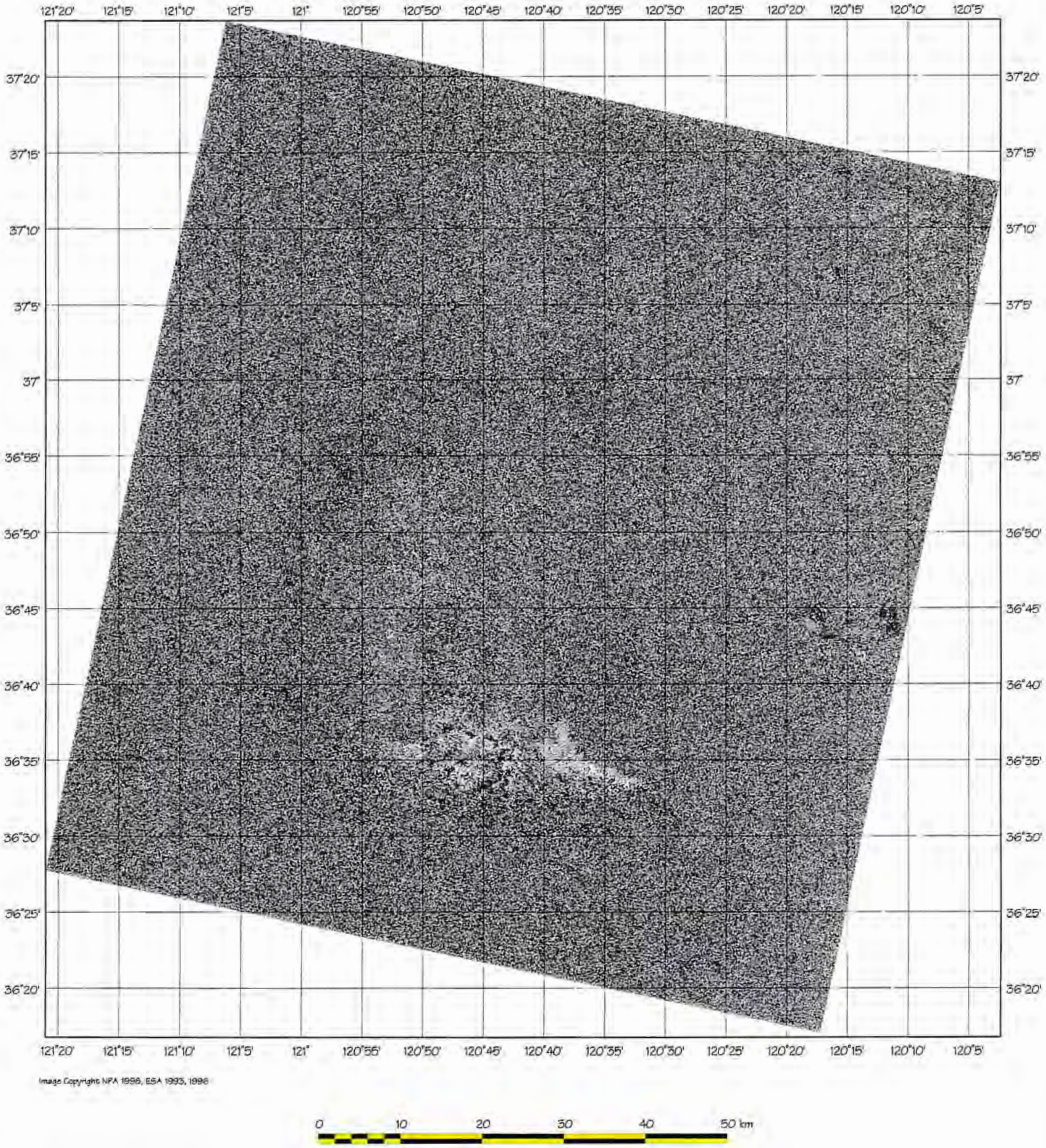
Differential interferogram for the Mendota, California area

ERS scene dates: 3 January 1993 & 17 January 1996
Temporal separation: 3 years
Perpendicular baseline: 27.7 m
Altitude of ambiguity: 339.9 m



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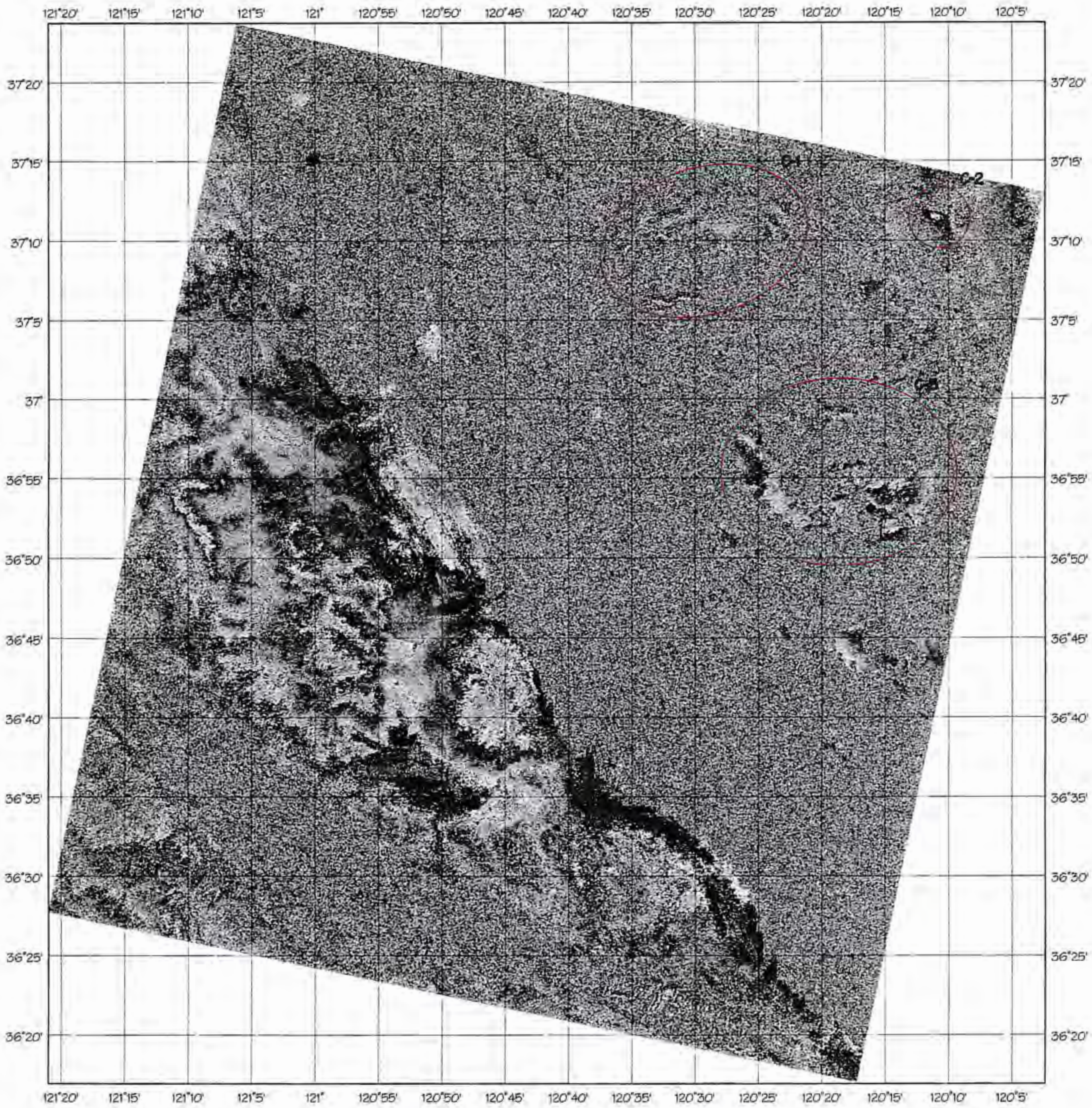
Differential interferogram for the Mendota, California area

ERS scene dates: 19 December 1993 & 4 October 1995
Temporal separation: 1 year 10 months
Perpendicular baseline: 21.2 m
Altitude of ambiguity: 441.2 m

Rings indicate fringe features in this image



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SAR & InSAR Processing Summary Report — **Mendota, California: MEN_1 & MEN_2**

1. Image Acquisition Dates:	3/1/93, 17/1/96
2. Temporal Separation:	3 years
3. Processing Stage (1[int], 2[diff] or 3[full]):	2
4. DEM details, if used:	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. SLC Processing:	
(i) Scene centre lat/long:	36° 50' 10" N, 120° 40' 55"W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	36° 50' 25" N,120° 44' 11" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	98.7 km × 107.1 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	23 m
(b) Derived from Precise State Vectors:	27.7 m
(iii) Altitude of Ambiguity:	339.9 m
(iv) Range × Azimuth extents:	98.8 km × 106.4 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	12.21
(ii) Standard Deviation:	8.15

9. Analysis/Interpretation of Results

The region is predominantly agricultural and/or vegetated. The coherence is effectively zero over the first interferogram and over almost the entire Mendota valley in the second interferogram, which has a shorter temporal separation.

Residual topographic phase effects can be observed in the first differential interferogram. This is thought to arise from a difference in atmospheric refraction characteristics between the two acquisitions, giving rise to a different effective interferometric baseline.

10. Conclusions/Recommendations

Despite the low coherence and baseline problems it is possible to see some evidence for surface movement in the valley at three locations. It would be desirable to reprocess this region using acquisitions with a smaller temporal separation.

Category	Label	Co-ordinates	Comments
3 class C features	C1	120° 30' W 37° 10' N	Possible spatially extended subsidence field > 4 cm/year
	C2	120° 11' W 37° 12' N	Possible localised (1 km) subsidence
	C3	120° 20' W 36° 55' N	Possible spatially extended subsidence field

Categories: **A** *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/Feature of interest*

SAR & InSAR Processing Summary Report **Mendota, California: MEN_3 & MEN_4**

1. **Image Acquisition Dates:**	19/12/93, 4/10/95
2. **Temporal Separation:**	1 year 10 months
3. **Processing Stage (1[int], 2[diff] or 3[full]):**	2
4. **DEM details, if used:**	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. **SLC Processing:**	
(i) Scene centre lat/long:	36° 50' 39" N, 120° 41' 49"W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. **Ground-range PRI (Amplitude Image) Processing:**	
(i) Scene centre lat/long:	36° 50' 55" N,120° 45' 8" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.9 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. **InSAR Processing**	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	27 m
(b) Derived from Precise State Vectors:	21.2 m
(iii) Altitude of Ambiguity:	441.2 m
(iv) Range × Azimuth extents:	99.3 km × 106.7 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. **Coherence Map Parameters**	
(i) Mean:	14.86
(ii) Standard Deviation:	11.09

9. Analysis/Interpretation of Results

The region is predominantly agricultural and/or vegetated. The coherence is effectively zero over the first interferogram and over almost the entire Mendota valley in the second interferogram, which has a shorter temporal separation.

Residual topographic phase effects can be observed in the first differential interferogram. This is thought to arise from a difference in atmospheric refraction characteristics between the two acquisitions, giving rise to a different effective interferometric baseline.

10. Conclusions/Recommendations

Despite the low coherence and baseline problems it is possible to see some evidence for surface movement in the valley at three locations. It would be desirable to reprocess this region using acquisitions with a smaller temporal separation.

Category	Label	Co-ordinates	Comments
3 class C features	C1	120° 30' W 37° 10' N	Possible spatially extended subsidence field > 4 cm/year
	C2	120° 11' W 37° 12' N	Possible localised (1 km) subsidence
	C3	120° 20' W 36° 55' N	Possible spatially extended subsidence field

Categories: **A** *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/Feature of interest*

Ventura, California — OVERALL RATING: 60%

1. Marketability — *Rating: Medium*

Randy Hanson has expressed strong interest in the study of Ventura and we believe that through him other commercial parties can be reached.

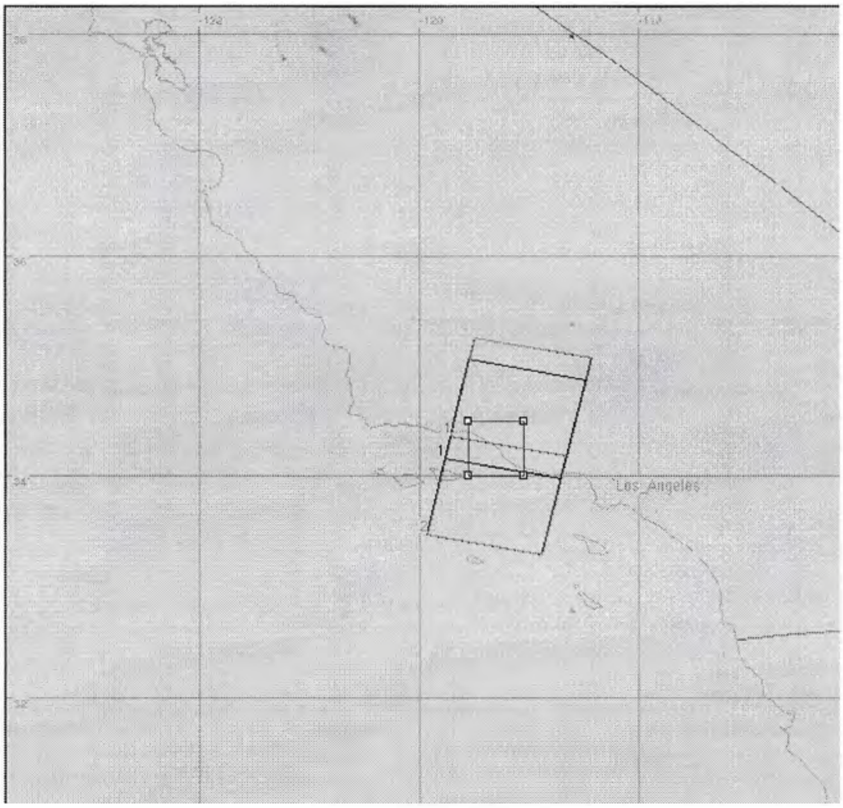
2. Subsidence category

Groundwater withdrawal.

3. Geographical extents and optimal ERS coverage

The extents of the Ventura area are approximately:

Longitude:	119° 0' W - 119° 30' W	(50 km)
Latitude:	34° 0' N - 34° 30' N	(50 km)



4. Socio-economic effects of subsidence

Unknown.

5. Customer / contact

Randy Hanson, Hydrologist, Water Resources Division, U.S. Geological Survey, San Diego, E-mail: rthanson@usgs.gov

Stanley A Leake, Research Hydrologist, Tucson, AZ, E-mail: saleake@usgs.gov

6. Subsidence rate/amount — *Rating: Low*

Unknown.

7. Ground-truth available — *Rating: Medium*

Randy Hanson has completed regional ground-water flow and subsidence models of the area that he is willing to make available to us.

8. Land cover — *Rating: Poor*

Small urban areas surrounded by agricultural land.

9. ERS data availability and status — *Rating: High*

No suitable ascending pairs.

Descending: 24 pairs with perpendicular baselines less than 50m and a temporal separation greater than a year.

Receiving Station: Prince Albert

10. DEM availability

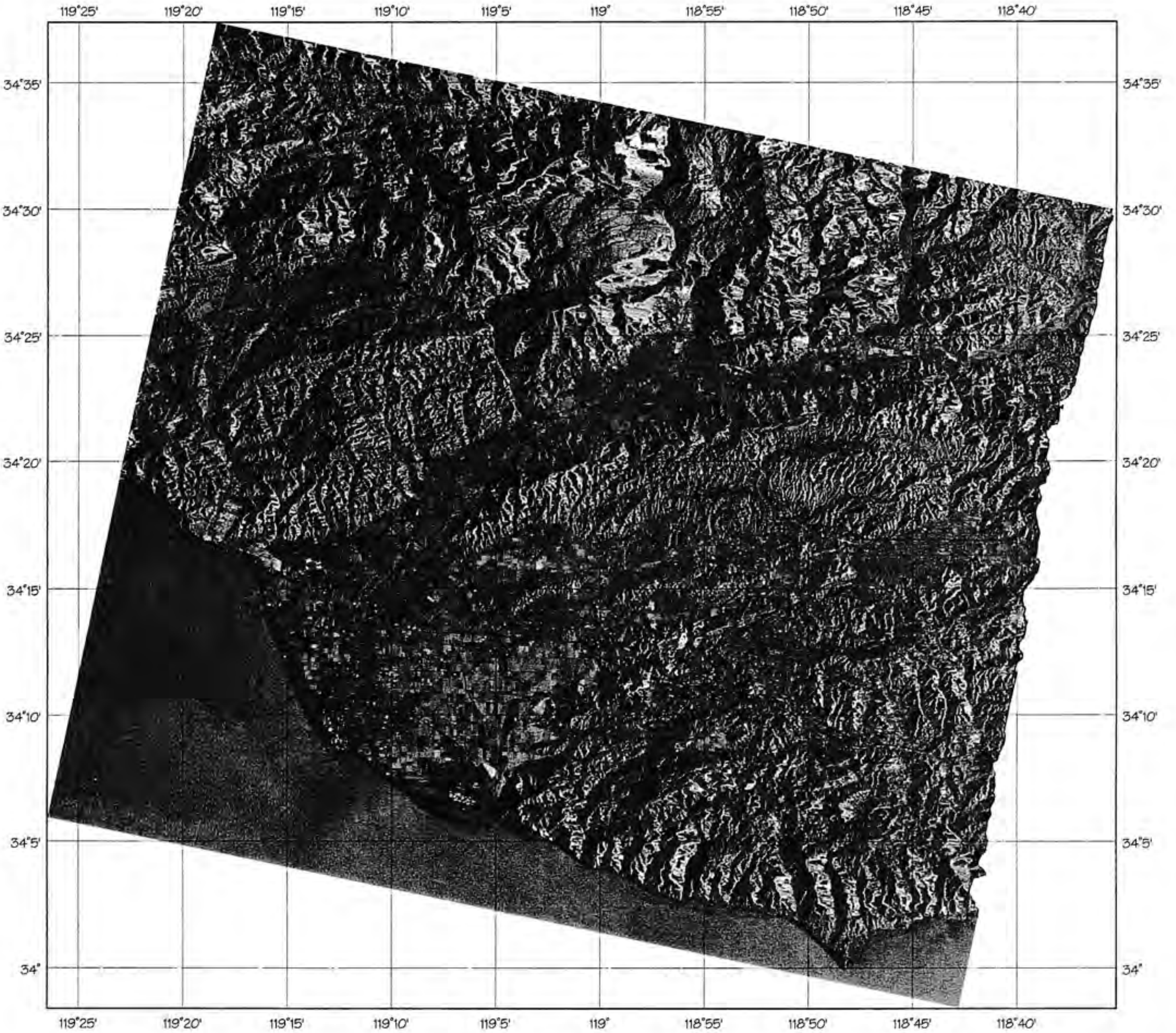
- USGS 1 arc second resolution xy and 20m z DEM available in 0.5° × 0.5° tiles.
  Cost approx. $100 for first tile, additional tiles much cheaper.
- USGS 3 arc second resolution xy and 20m z DEM for the whole of the US held in-house.
- GTOPO-30 coarse 1km resolution DEM of variable quality held in-house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in-house yet.
- Tandem InSAR.

11. Processing status

Three differential interferograms produced.

Radar amplitude image for the Ventura, California area

ERS scene date: 12 December 1992



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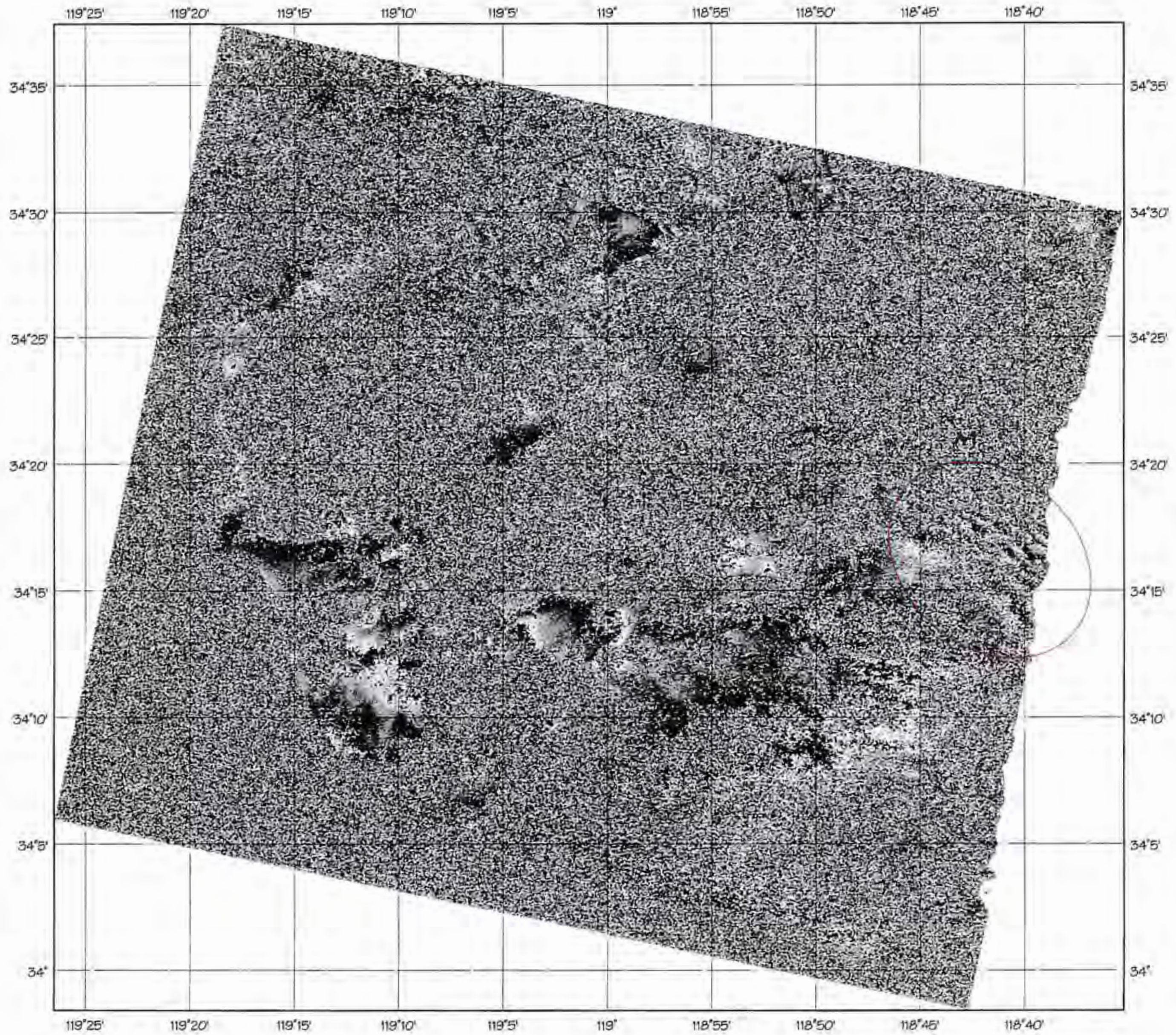
Differential interferogram for the Ventura, California area

ERS scene dates: 12 December 1992 & 29 January 1996
Temporal separation: 3 years 1 month
Perpendicular baseline: 3.0 m
Altitude of ambiguity: 3138.7 m

Rings indicate fringe features in this image



NPA SATELLITE MAPPING

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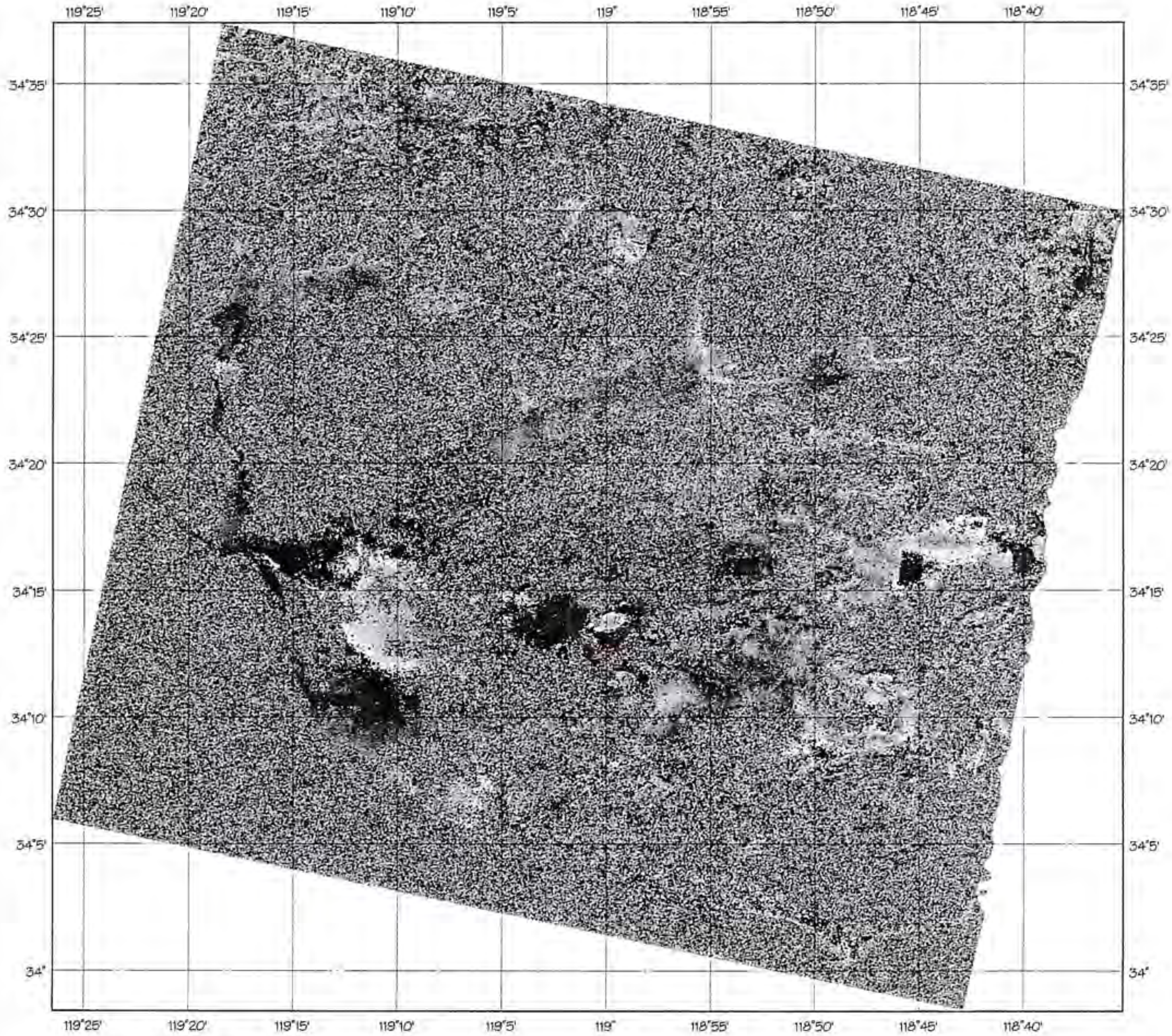
Differential interferogram for the Ventura, California area

ERS scene dates: 29 January 1996 & 14 January 1997
Temporal separation: 1 year
Perpendicular baseline: 80.0 m
Altitude of ambiguity: 117.7 m

Rings indicate fringe features in this image



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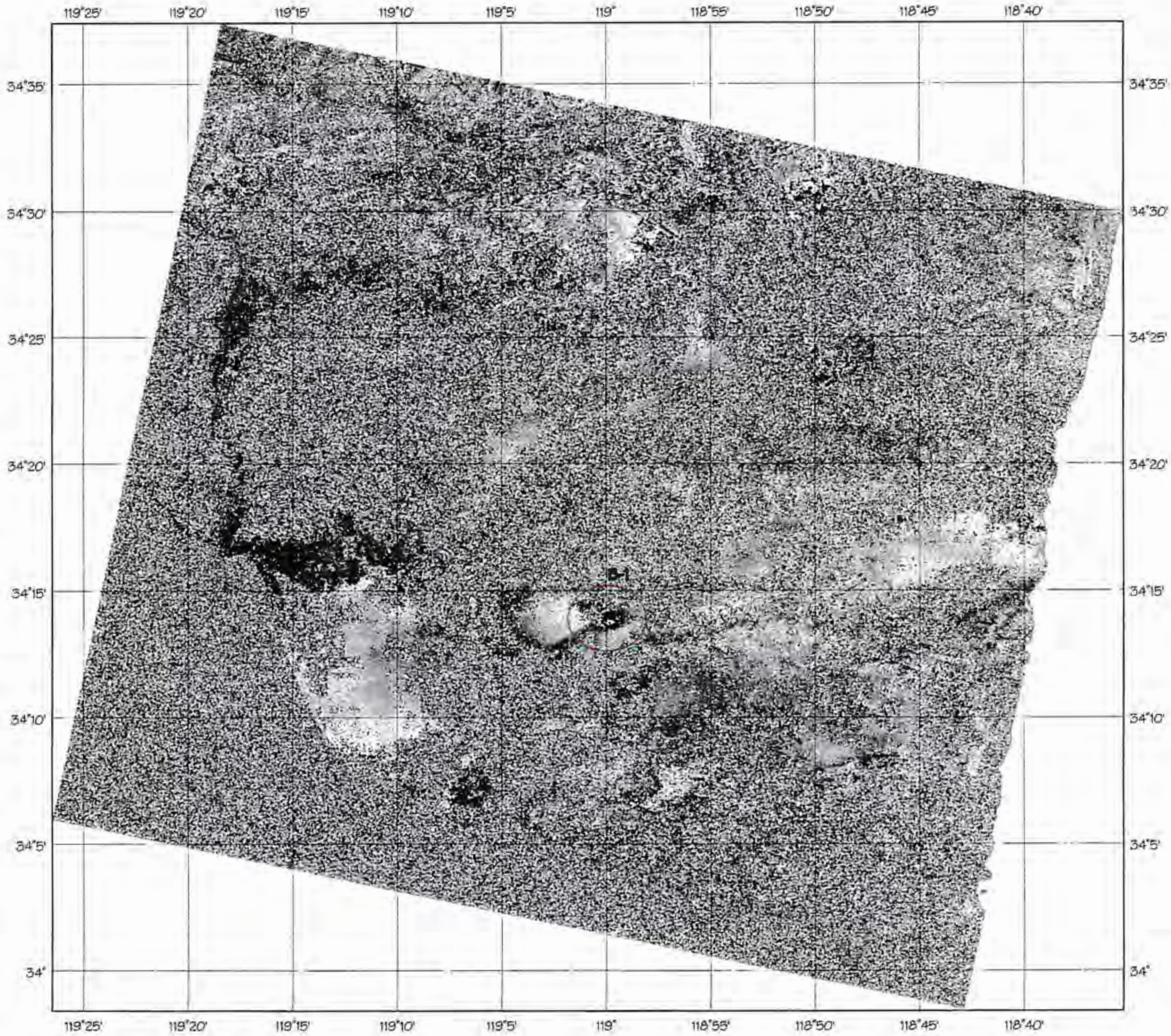
Differential interferogram for the Ventura, California area

ERS scene dates: 29 January 1996 & 30 December 1997
Temporal separation: 1 year 11 months
Perpendicular baseline: 26.4 m
Altitude of ambiguity: 356.7 m

Rings indicate fringe features in this image



NPA SATELLITE MAPPING

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SAR & InSAR Processing Summary Report | **Ventura, California: VET_1 & VET_2**

1. Image Acquisition Dates:	12/12/92, 29/1/96
2. Temporal Separation:	3 years 1 month
3. Processing Stage (1[int], 2[diff] or 3[full]):	2
4. DEM details, if used:	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. SLC Processing:	
(i) Scene centre lat/long:	34° 31' 05" N, 119° 07' 09"W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	34° 31' 18" N,119° 10' 14" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	97.6 km × 107.1 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	16 m
(b) Derived from Precise State Vectors:	3.0 m
(iii) Altitude of Ambiguity:	3138.7 m
(iv) Range × Azimuth extents:	97.9 km × 107.0 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	15.31
(ii) Standard Deviation:	11.03

9. Analysis/Interpretation of Results

Data Specifications - Interferogram A
ERS acquisitions: 12-Dec-92 and 29-Jan-96
Temporal separation: 3 years 1 month
Perpendicular baseline: 3 m

Data Specifications - Interferogram B
ERS acquisitions: 29-Jan-96 and 14-Jan-97
Temporal separation: 1 year
Perpendicular baseline: 80 m

Data Specifications - Interferogram C
ERS acquisitions: 29-Jan-96 and 30-Dec-97
Temporal separation: 1 year 11 months
Perpendicular baseline: 26 m

The Ventura region is well vegetated and the coherence on each of this triplet of differential interferograms is generally low.

Only one small (1 km-diameter) region has been identified exhibiting a consistent subsidence signature. The only other feature identified is the faint trace of a segment of the uplift field associated with the Northridge earthquake.

10. Conclusions/Recommendations

Category	Label	Co-ordinates	Comments
1 class A feature	A1 (interferogram A)	118° 41' W 34° 17' N	Northridge earthquake
1 class B feature	B1	118° 59' 30" W 34° 14' N	Localised subsidence <1-2 cm/year

Categories: A *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/Feature of interest*

SAR & InSAR Processing Summary Report — **Ventura, California: VET_2 & VET_3**

1. Image Acquisition Dates:	29/1/96, 14/1/97
2. Temporal Separation:	1 year
3. Processing Stage (1[int], 2[diff] or 3[full]):	2
4. DEM details, if used:	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. SLC Processing:	
(i) Scene centre lat/long:	34° 30' 58" N, 119° 07' 23"W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	34° 31' 12" N,119° 10' 13" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	97.8 km × 107.0 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	84 m
(b) Derived from Precise State Vectors:	80.0 m
(iii) Altitude of Ambiguity:	117.7 m
(iv) Range × Azimuth extents:	97.9 km × 106.9 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	17.48
(ii) Standard Deviation:	12.83

9. Analysis/Interpretation of Results

Data Specifications - Interferogram A
ERS acquisitions: 12-Dec-92 and 29-Jan-96
Temporal separation: 3 years 1 month
Perpendicular baseline: 3 m

Data Specifications - Interferogram B
ERS acquisitions: 29-Jan-96 and 14-Jan-97
Temporal separation: 1 year
Perpendicular baseline: 80 m

Data Specifications - Interferogram C
ERS acquisitions: 29-Jan-96 and 30-Dec-97
Temporal separation: 1 year 11 months
Perpendicular baseline: 26 m

The Ventura region is well vegetated and the coherence on each of this triplet of differential interferograms is generally low.

Only one small (1 km-diameter) region has been identified exhibiting a consistent subsidence signature. The only other feature identified is the faint trace of a segment of the uplift field associated with the Northridge earthquake.

10. Conclusions/Recommendations

Category	Label	Co-ordinates	Comments
1 class A feature	A1 (interferogram A)	118° 41' W 34° 17' N	Northridge earthquake
1 class B feature	B1	118° 59' 30" W 34° 14' N	Localised subsidence <1-2 cm/year

Categories: **A** *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/Feature of interest*

SAR & InSAR Processing Summary Report **Ventura, California: VET_2 & VET_4**

1. Image Acquisition Dates:	29/1/96, 30/12/97
2. Temporal Separation:	1 year 11 months
3. Processing Stage (1[int], 2[diff] or 3[full]):	2
4. DEM details, if used:	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. SLC Processing:	
(i) Scene centre lat/long:	34° 30' 57" N, 119.123° W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	34° 31' 12" N,119° 10' 13" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	97.5 km × 107.1 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	25 m
(b) Derived from Precise State Vectors:	26.4 m
(iii) Altitude of Ambiguity:	356.7 m
(iv) Range × Azimuth extents:	97.9 km × 106.8 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	17.12
(ii) Standard Deviation:	12.72

9. Analysis/Interpretation of Results

Data Specifications - Interferogram A
ERS acquisitions: 12-Dec-92 and 29-Jan-96
Temporal separation: 3 years 1 month
Perpendicular baseline: 3 m

Data Specifications - Interferogram B
ERS acquisitions: 29-Jan-96 and 14-Jan-97
Temporal separation: 1 year
Perpendicular baseline: 80 m

Data Specifications - Interferogram C
ERS acquisitions: 29-Jan-96 and 30-Dec-97
Temporal separation: 1 year 11 months
Perpendicular baseline: 26 m

The Ventura region is well vegetated and the coherence on each of this triplet of differential interferograms is generally low.

Only one small (1 km-diameter) region has been identified exhibiting a consistent subsidence signature. The only other feature identified is the faint trace of a segment of the uplift field associated with the Northridge earthquake.

10. Conclusions/Recommendations

Category	Label	Co-ordinates	Comments
1 class A feature	A1 (interferogram A)	118° 41' W 34° 17' N	Northridge earthquake
1 class B feature	B1	118° 59' 30" W 34° 14' N	Localised subsidence <1-2 cm/year

Categories: A *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/Feature of interest*

Las Vegas Valley, Nevada OVERALL RATING: 80%

1. Marketability *Rating: Medium*

Las Vegas has a history of expensive repairs to subsidence damaged property. It is the most rapidly growing metropolitan area in the U.S. (1995 Census Bureau report) and its population is dependent to a large degree on groundwater for domestic use.

2. Subsidence category

Groundwater abstraction.

3. Geographical extents and optimal ERS coverage

From previous surveys the extent of the subsidence is approximately:

Longitude:	114° 50' W - 115° 33' W	(70 km)
Latitude:	35° 55' N - 36° 30' N	(70 km)

4. Socio-economic effects of subsidence

In 1989, the U.S. Department of Housing and Urban Development began making special subsidence hazard assessments a requirement for property located in close proximity to known subsidence features. This requirement was primarily a consequence of the structural damage caused by fissuring in the Windsor Park subdivision of North Las Vegas; estimated total costs for repair or replacement of more than 240 damaged or threatened homes in this area were $12-13 million.

5. Customer / contact

Mr. Donald Helm, Morgan State University, Maryland, E-mail: helm@eng.morgan.edu

Prof. John Bell, , Nevada Bureau of Mines and Geology, University of Nevada-Reno,
E-mail: jbell@nbmg.unr.edu

Falk Amelung, Department of Geophysics, Stanford University, Stanford,
E-mail: amelung@pangea.stanford.edu

Devin Galloway U.S. Geological Survey, Sacramento, E-mail: dlgallow@usgs.gov

6. Subsidence rate/amount *Rating: Medium*

Subsidence of 10cm observed for the period 1992-96 by the USGS with interferometry.

7. Ground-truth available *Rating: Medium*

New GPS survey scheduled for this year, previous survey is 1990/1991.

8. Land cover *Rating: Good*

Urban area surrounded by desert land.

9. ERS Data availability and status *Rating: High*

No suitable ascending pairs.
Descending: 12 pairs with perpendicular baselines less than 50m and a temporal separation greater than a year.

Receiving station: Prince Albert

10. DEM availability

- USGS 1 arc second resolution xy and 20m z DEM available in 0.5° × 0.5° tiles.
  Cost approx. $100 for first tile, additional tiles much cheaper.
- USGS 3 arc second resolution xy and 20m z DEM for the whole of the US held in-house.
- GTOPO-30 coarse 1km resolution DEM of variable quality held in-house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in-house yet.
- Tandem InSAR.

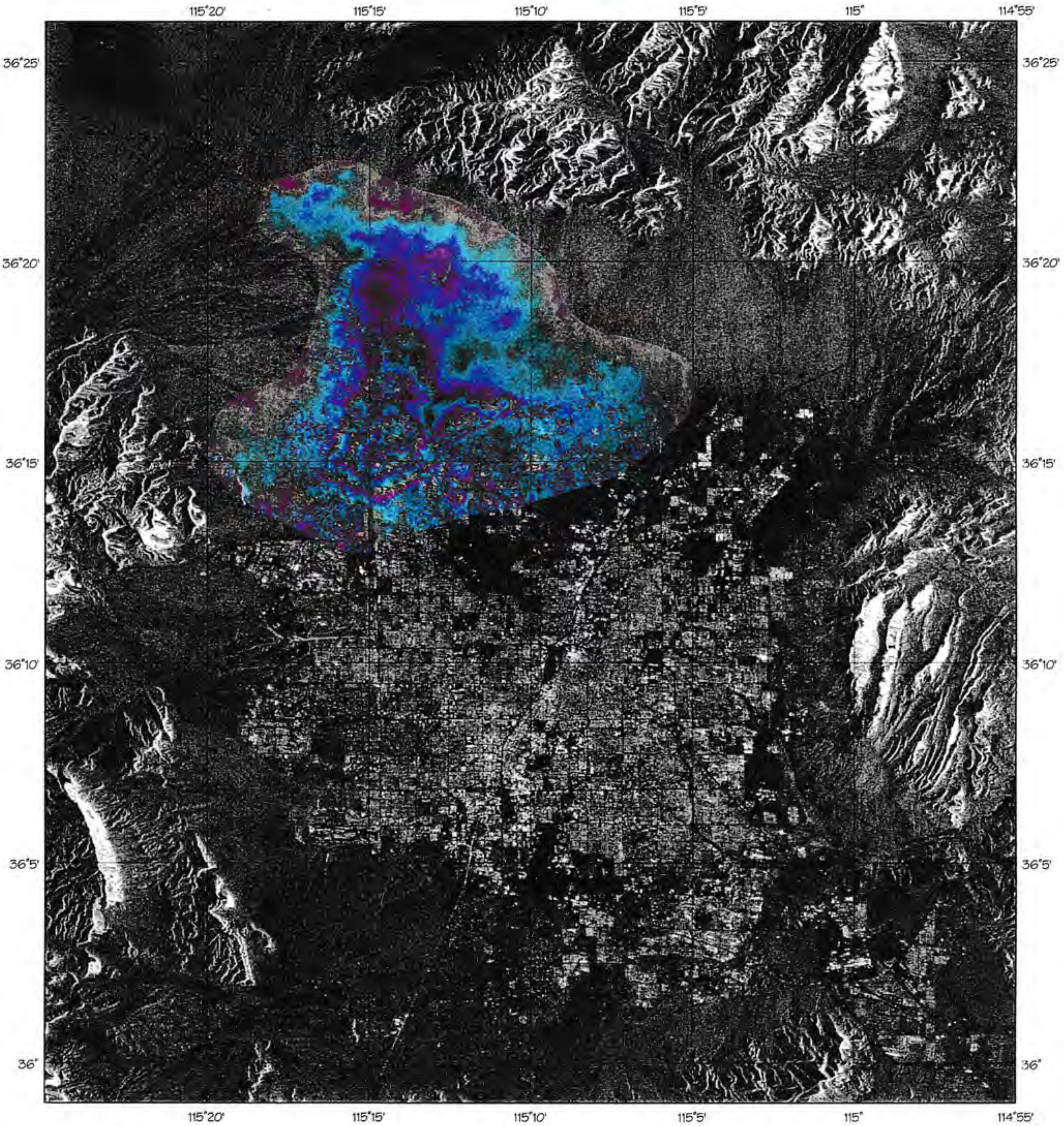
11. Processing status

Two differential interferograms produced.

Interferometric subsidence fringes for the Las Vegas, Nevada area (Differential interferogram over ERS radar amplitude image)

ERS scene dates: 6 April 1993 & 18 April 1996
Temporal separation: 3 years
Perpendicular baseline: 35.0 m
Altitude of ambiguity: 269.0 m

Ground displacement per fringe cycle in ERS line of sight: 0 cm — 1.4 cm — 2.8 cm



0 5 10 15 20 25 km

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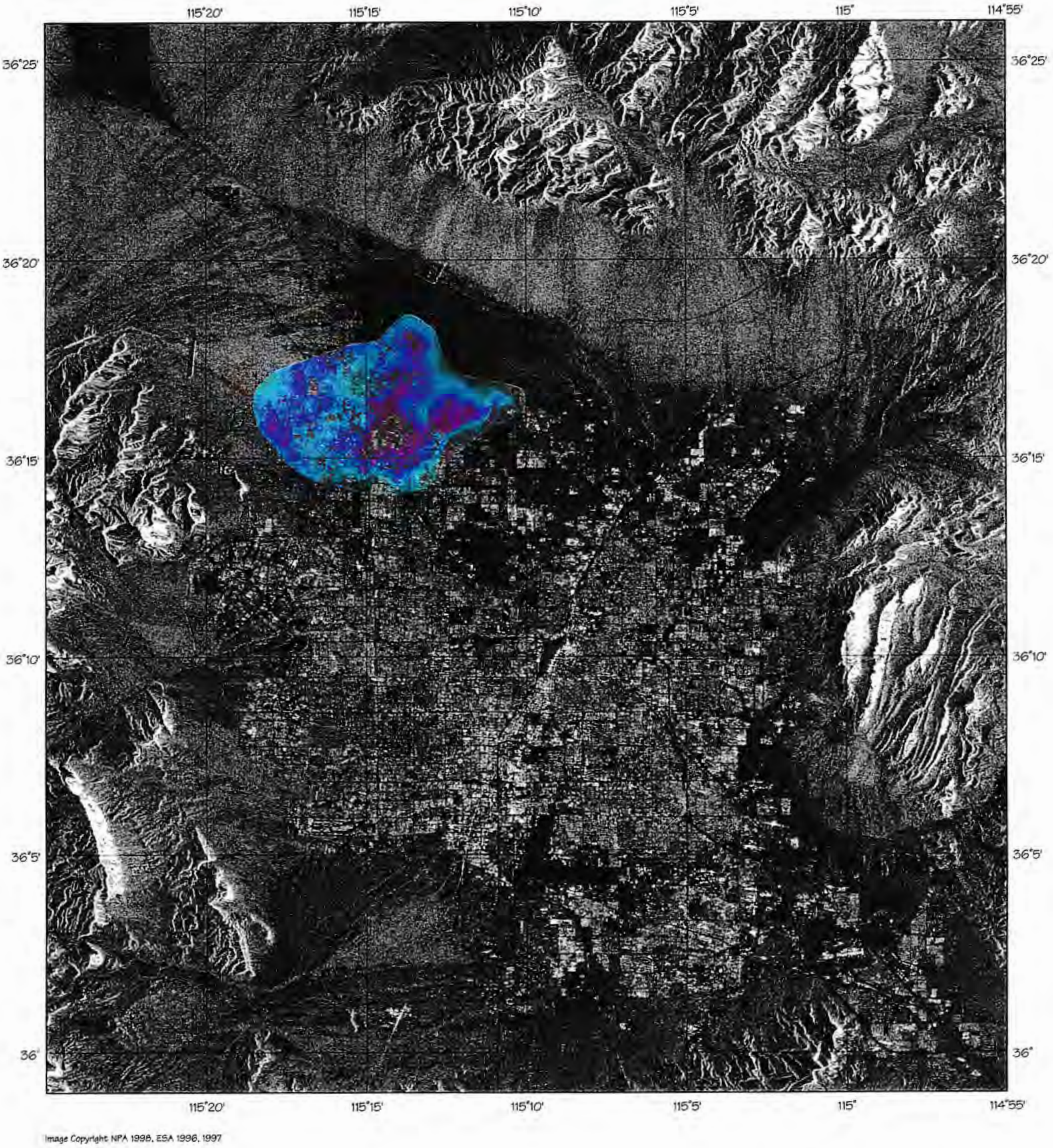
Interferometric subsidence fringes for the Las Vegas, Nevada area (Differential interferogram over ERS radar amplitude image)

ERS scene dates: 23 May 1996 & 13 June 1997
Temporal separation: 1 year 1 month
Perpendicular baseline: 103.5 m
Altitude of ambiguity: 91.0 m

Ground displacement per fringe cycle in ERS line of sight: 0 cm — 1.4 cm — 2.8 cm



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SAR & InSAR Processing Summary Report **Las Vegas, Nevada: LAS_1 & LAS_2**

1. Image Acquisition Dates:	6/4/93, 18/4/96
2. Temporal Separation:	3 years
3. Processing Stage (1[int], 2[diff] or 3[full]):	3
4. DEM details, if used:	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. SLC Processing:	
(i) Scene centre lat/long:	36° 20' 57" N, 115° 04' 48"W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	36° 21' 15" N,115° 8' 25" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	98.8 km ×107.0 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	30 m
(b) Derived from Precise State Vectors:	35.0 m
(iii) Altitude of Ambiguity:	269.0 m
(iv) Range × Azimuth extents:	107.0 km × 99.0 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	34.97
(ii) Standard Deviation:	20.88

9. Analysis/Interpretation of Results

These two differential interferograms are the least satisfactory products generated to date, exhibiting both large-scale phase trends and localised anomalies. Some attempt has been made to remove the worst of the phase trends, with very limited success. A number of checks have been made on the processing chain, and we are satisfied that the phase variations are a feature of the data as opposed to artefacts of the data processing or the digital elevation models. The effects are presumed to derive from significant and inhomogeneous variations in atmospheric refraction. It appears to be generally the case that interferometric data acquired over the arid regions of the Southwest USA is less stable than that acquired over Europe, and there may be some physical connection between temperature range and atmospheric stability.

Despite the poor quality of the interferometric data, subsidence is however clearly evident in a localised region of size 10 km by 5 km to the Northeast of Las Vegas, as shown in the extracts in the preceding pages. The maximum subsidence is around 9 cm over 3 years and the rate of subsidence of 3 cm/year appears to be consistent between the two interferograms.

10. Conclusions/Recommendations

Category	Label	Co-ordinates	Comments
1 class A feature	A1	115° 14' W 36° 16' N	3 cm/year subsidence field, size 10 km by 5 km

Categories: **A** *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/Feature of interest*

SAR & InSAR Processing Summary Report **Las Vegas, Nevada: LAS_3 & LAS_4**

1. Image Acquisition Dates:	23/5/96, 3/6/97
2. Temporal Separation:	1 year 1 month
3. Processing Stage (1[int], 2[diff] or 3[full]):	3
4. DEM details, if used:	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. SLC Processing:	
(i) Scene centre lat/long:	36° 20' 49" N, 115° 04' 23"W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	34° 12' 17" N, 118° 32' 14"W
(ii) Full- (or sub-) scene Range × Azimuth extents:	99.7 km × 107.0 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	45 m
(b) Derived from Precise State Vectors:	103.5 m
(iii) Altitude of Ambiguity:	91.0 m
(iv) Range × Azimuth extents:	99.23 km × 101.3 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	46.57
(ii) Standard Deviation:	27.50

9. Analysis/Interpretation of Results

These two differential interferograms are the least satisfactory products generated to date, exhibiting both large-scale phase trends and localised anomalies. Some attempt has been made to remove the worst of the phase trends, with very limited success. A number of checks have been made on the processing chain, and we are satisfied that the phase variations are a feature of the data as opposed to artefacts of the data processing or the digital elevation models. The effects are presumed to derive from significant and inhomogeneous variations in atmospheric refraction. It appears to be generally the case that interferometric data acquired over the arid regions of the Southwest USA is less stable than that acquired over Europe, and there may be some physical connection between temperature range and atmospheric stability.

Despite the poor quality of the interferometric data, subsidence is however clearly evident in a localised region of size 10 km by 5 km to the Northeast of Las Vegas, as shown in the extracts in the preceding pages. The maximum subsidence is around 9 cm over 3 years and the rate of subsidence of 3 cm/year appears to be consistent between the two interferograms.

10. Conclusions/Recommendations

Category	Label	Co-ordinates	Comments
1 class A feature	A1	115° 14' W 36° 16' N	3 cm/year subsidence field, size 10 km by 5 km

Categories: **A** *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/Feature of interest*

Reno, Nevada OVERALL RATING: 60%

1. Marketability *Rating: Medium*

Large urban area suffering from subsidence.

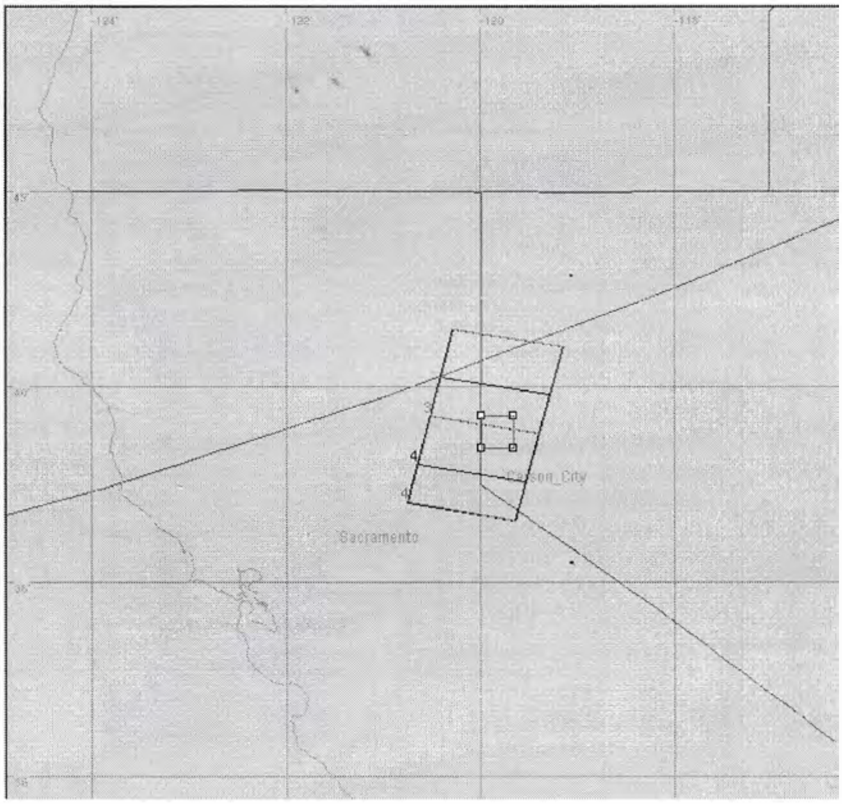
2. Subsidence category

Groundwater abstraction.

3. Geographical extents and optimal ERS coverage

The extents of the Reno area are approximately:

Longitude:	119° 39' W - 119° 59' W	(20 km)
Latitude:	39° 21' N - 39° 42' N	(20 km)



4. Socio-economic effects of subsidence

Unknown.

5. Customer / contact

Don Helm, Nevada Bureau of Mines and Geology, University of Nevada-Reno,
E-mail: helm@eng.morgan.edu

6. Subsidence rate/amount — Rating: Low

Unknown.

7. Ground-truth available — Rating: Poor

Unknown.

8. Land cover — Rating: Medium

Large urban area.

9. ERS data availability and status — Rating: High

No suitable ascending pairs.
Descending: 27 pairs with perpendicular baselines less than 50m and a temporal separation greater than a year.

Receiving Station: Prince Albert

10. DEM availability

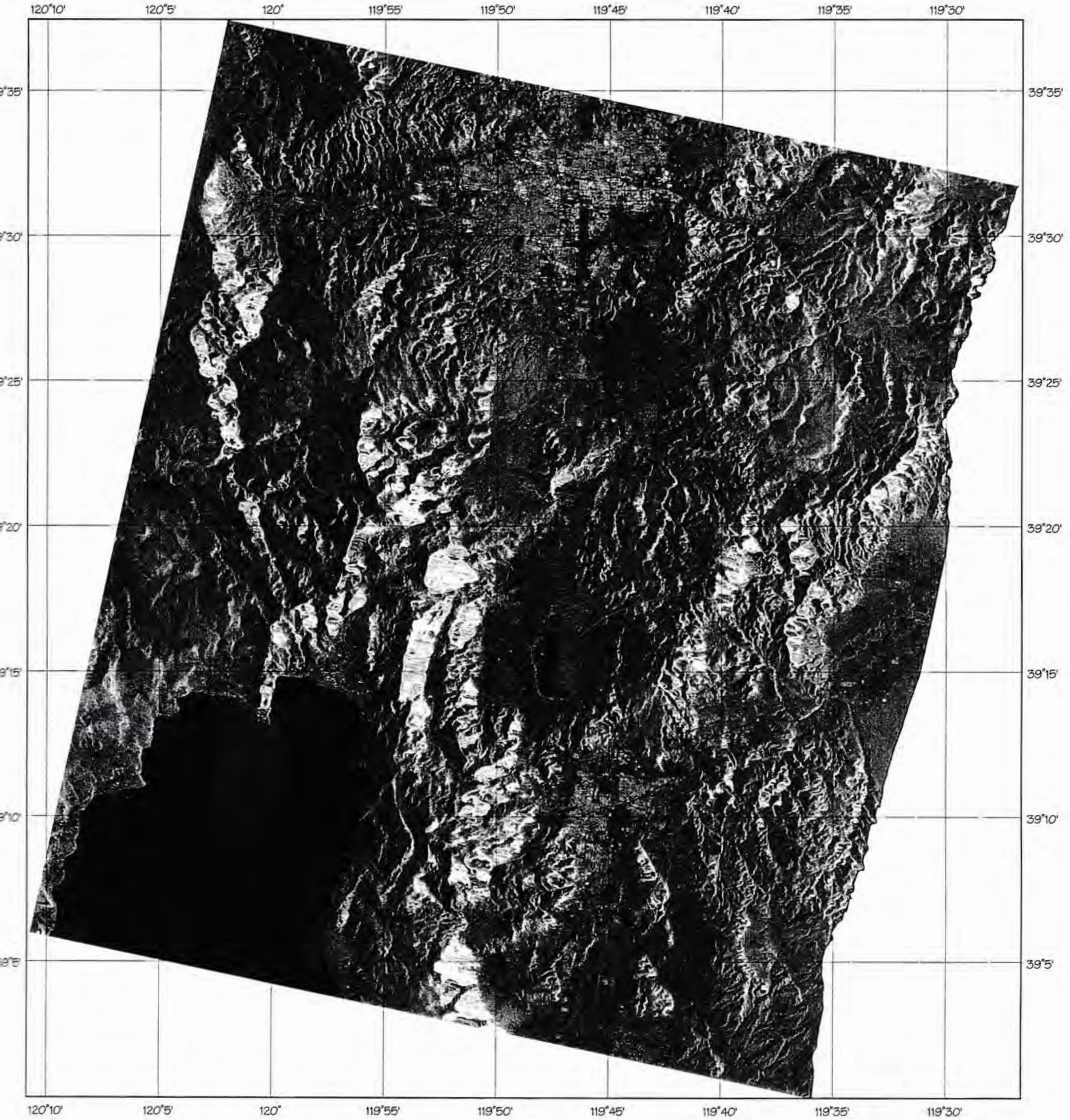
- USGS 1 arc second resolution xy and 20m z DEM available in 0.5° × 0.5° tiles. Cost approx. $100 for first tile, additional tiles much cheaper.
- USGS 3 arc second resolution xy and 20m z DEM for the whole of the US held in-house.
- GTOPO-30 coarse 1km resolution DEM of variable quality held in-house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in-house yet.
- Tandem InSAR.

11. Processing status

Differential interferogram produced.

Radar amplitude image for the Reno, Nevada area

ERS scene date: 5 September 1993



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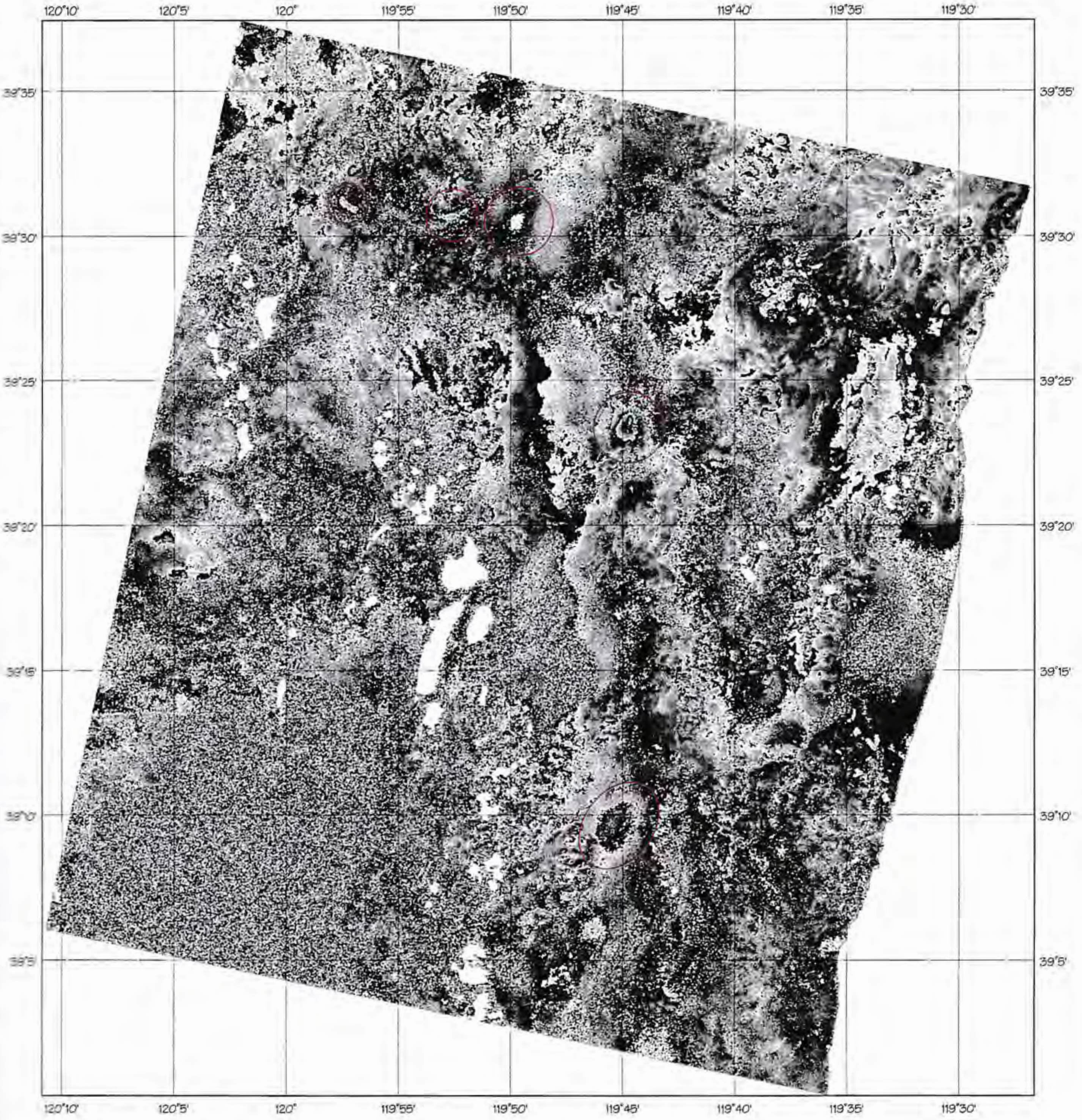
Differential interferogram for the Reno, Nevada area

ERS scene dates: 5 September 1993 & 8 November 1995
Temporal separation: 2 years 2 months
Perpendicular baseline: 59.6 m
Altitude of ambiguity: 160.0 m

Rings indicate fringe features in this image



0 5 10 15 20 25 km

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SAR & InSAR Processing Summary Report — **Reno, Nevada: REN_1 & REN_2**

1. Image Acquisition Dates:	5/9/93, 8/11/95
2. Temporal Separation:	2 years 2 months
3. Processing Stage (1[int], 2[diff] or 3[full]):	2
4. DEM details, if used:	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. SLC Processing:	
(i) Scene centre lat/long:	39° 33' 29" N, 119° 58' 30"W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	39° 33' 51" N,120° 2' 17" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	97.2 km × 107.0 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	64 m
(b) Derived from Precise State Vectors:	59.6 m
(iii) Altitude of Ambiguity:	160.0 m
(iv) Range × Azimuth extents:	97.4 km × 106.8 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	20.76
(ii) Standard Deviation:	16.73

9. Analysis/Interpretation of Results

This differential interferogram exhibits good overall coherence but a high level of atmospheric phase noise, making interpretation difficult.

Despite the noise a number of small but potentially significant features can be observed in the Reno urban area. These features are identified as much on the basis of shape as the magnitude of phase perturbation. There is no evidence of any extended region with subsidence at a high rate.

10. Conclusions/Recommendations

Category	Label	Co-ordinates	Comments
2 class B features	B1	119° 45' W 39° 23' N	2 km diameter subsidence < 3 cm/year
	B2	119° 49' W 39° 31' N	Localised subsidence < 0.5 cm/year
3 class C features	C1	119° 57' W 39° 31' N	Localised subsidence < 0.5-1 cm/year
	C2	119° 53' W 39° 31' N	Localised subsidence < 0.5-1 cm/year
	C3	119° 45' W 39° 09' 30" N	1.5 km diameter uplift < 0.5-1 cm/year

Categories: **A** *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/Feature of interest*

A repeat analysis with different acquisitions would be desirable to confirm the apparent ground movement at these sites.

Albuquerque, New Mexico — OVERALL RATING: 53%

1. Marketability — *Rating: Medium*

Groundwater withdrawals have caused depletions in the aquifer system storage and reductions of surface water flow in the Rio Grande. Charles Heywood (see below) is involved in the monitoring of subsidence and groundwater use.

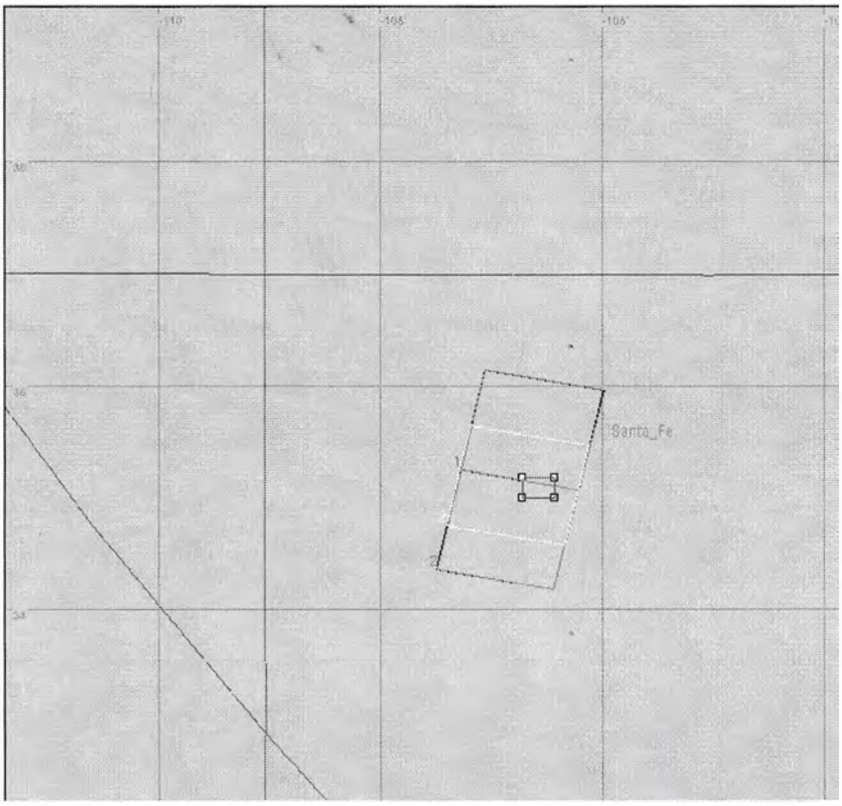
2. Subsidence category

Groundwater withdrawal.

3. Geographical extents and optimal ERS coverage

The extents of the Albuquerque area are approximately:

Longitude:	106° 26' W - 106° 43' W	(20 km)
Latitude:	35° 0' N - 35° 11' N	(10 km)



4. Socio-economic effects of subsidence

Unknown.

5. Customer / contact

Charles E. Heywood, U.S. Geological Survey, Albuquerque, NM, E-mail: cheywood@usgs.gov

6. Subsidence rate/amount — *Rating: Low*

Current rate of subsidence unknown.

7. Ground-truth available — *Rating: Poor*

No ground-truth information is currently available.

8. Land cover — *Rating: Medium*

Semi-arid landscape with medium sized urban area and some agriculture.

9. ERS data availability and status — *Rating: Medium*

No suitable ascending pairs.
Descending: 10 pairs with perpendicular baselines less than 50m and a temporal separation greater than a year.

Receiving Station: Prince Albert

10. DEM availability

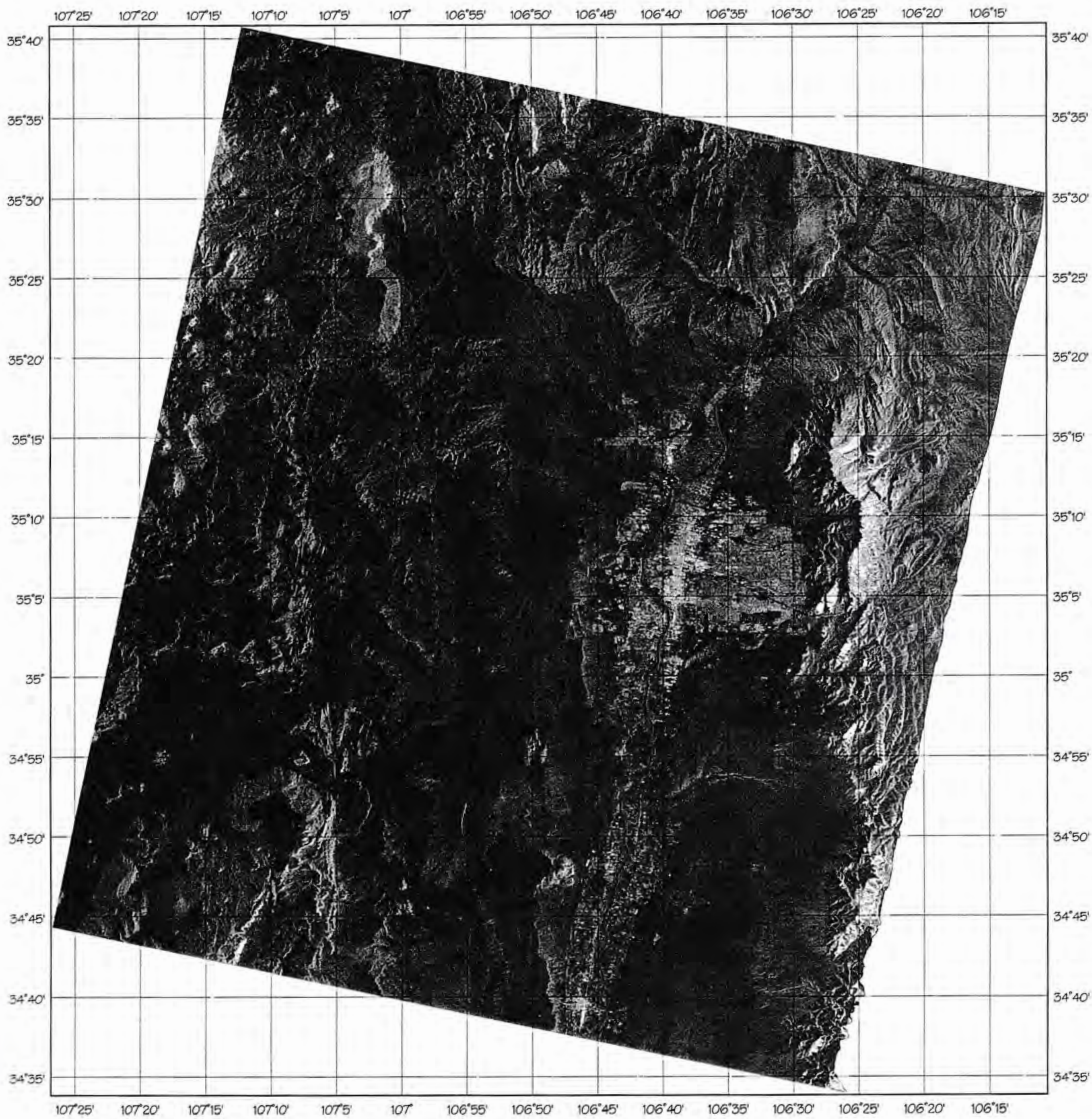
- USGS 1 arc second resolution xy and 20m z DEM available in 0.5° × 0.5° tiles. Cost approx. $100 for first tile, additional tiles much cheaper.
- USGS 3 arc second resolution xy and 20m z DEM for the whole of the US held in-house.
- GTOPO-30 coarse 1km resolution DEM of variable quality held in-house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in-house yet.
- Tandem InSAR.

11. Processing status

Differential interferogram produced.

Radar amplitude image for the Albuquerque, New Mexico area

ERS scene date: 12 November 1995



0 10 20 30 40 50 km

NPA SATELLITE MAPPING

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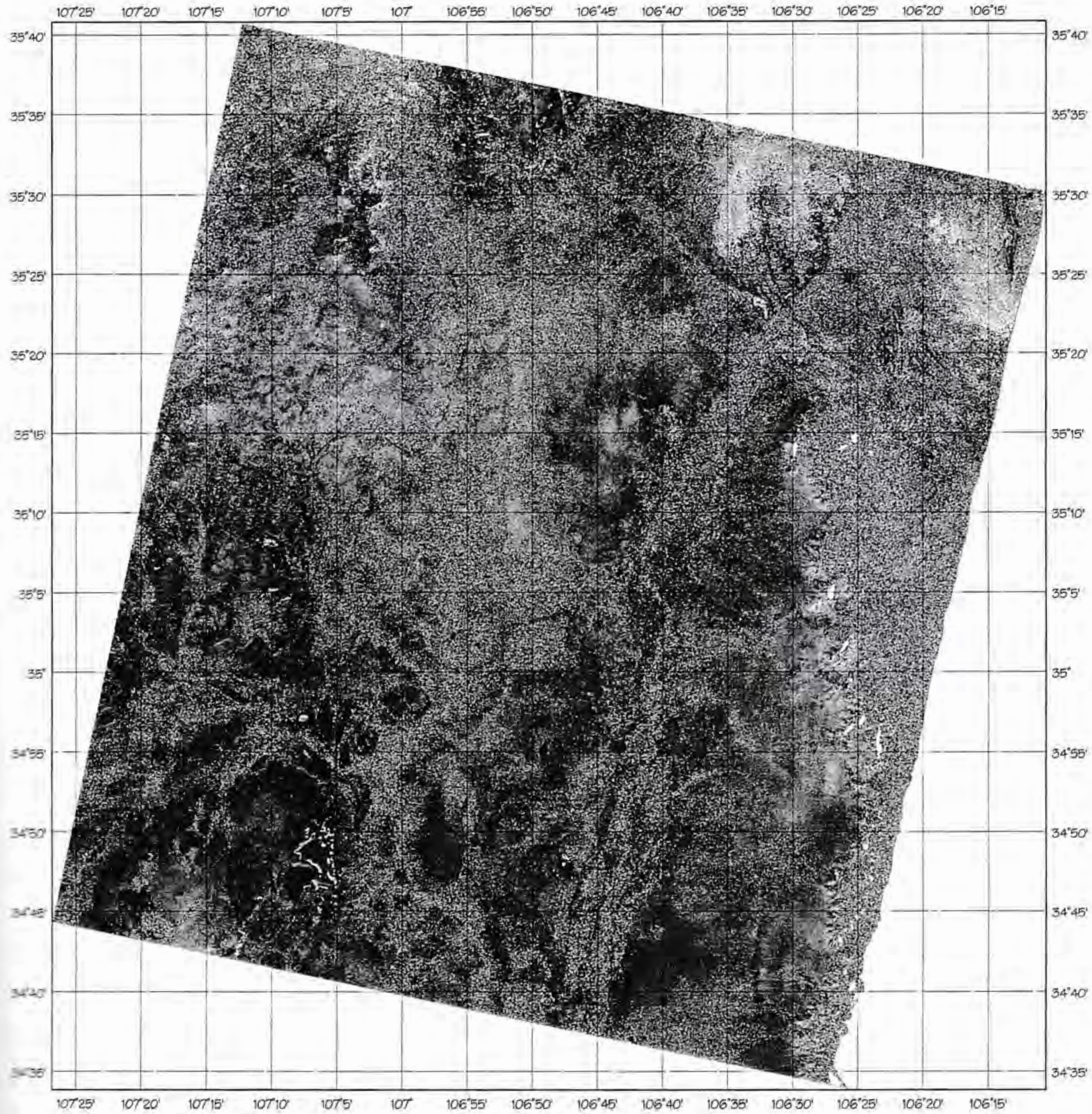
Differential interferogram for the Albuquerque, New Mexico area

ERS scene dates: 12 November 1995 & 17 November 1997
Temporal separation: 2 years
Perpendicular baseline: 48.50 m
Altitude of ambiguity: 194.14 m



Supported by

SAR & InSAR Processing Summary Report **Albuquerque, New Mexico: ALB_1 & ALB_2**

1. Image Acquisition Dates:	12/11/95, 17/11/97
2. Temporal Separation:	2 years
3. Processing Stage (1[int], 2[diff] or 3[full]):	2
4. DEM details, if used:	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. SLC Processing:	
(i) Scene centre lat/long:	35° 06' 57"N, 106° 46' 19"W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	35° 7' 20"N, 106° 50' 13"W
(ii) Full- (or sub-) scene Range × Azimuth extents:	95.8 km × 107.0 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	48 m
(b) Derived from Precise State Vectors:	48.50 m
(iii) Altitude of Ambiguity:	194.14 m
(iv) Range × Azimuth extents:	96.1 km × 107.0 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	16.23
(ii) Standard Deviation:	12.92

9. Analysis/Interpretation of Results

The quality of this differential interferogram is generally good, with no significant atmospheric or other artefacts, and with good coherence over non-cultivated areas.

10. Conclusions/Recommendations

There is no evidence for any significant surface movement on this data.

Mimbres Basin, New Mexico — OVERALL RATING: 73%

1. Marketability — *Rating: Medium*

The Mimbres Basin has suffered from land subsidence and earth fissuring since the 1950's as a consequence of groundwater abstraction for irrigation and domestic use.
No previous study of the subsidence has been conducted using interferometry and great interest in the work has been expressed by two contacts at the USGS.

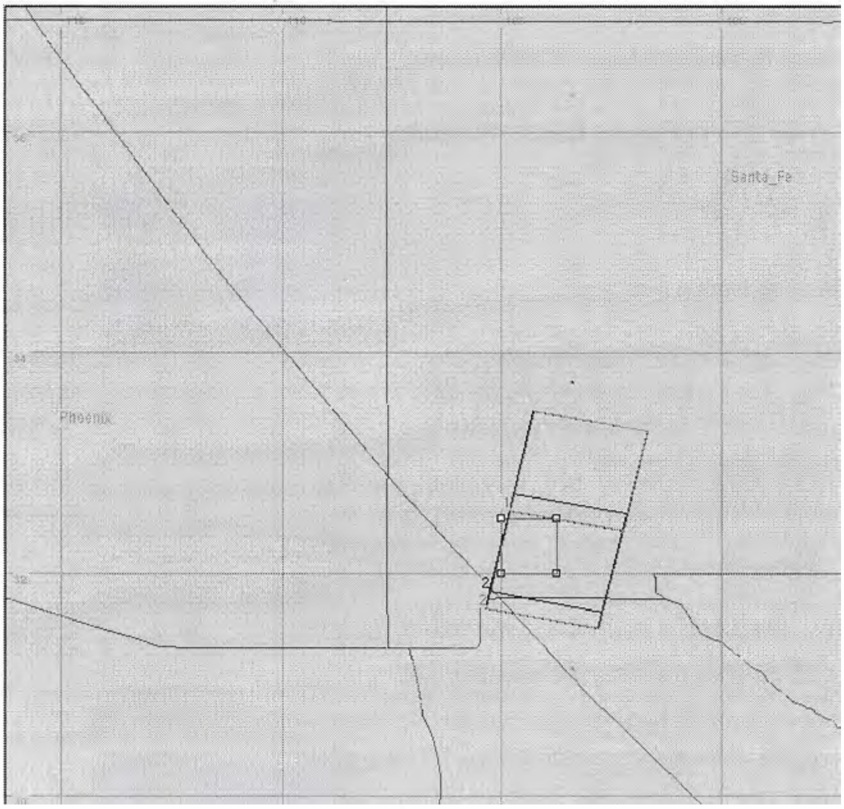
2. Subsidence category

Groundwater abstraction.

3. Geographical extents and optimal ERS coverage

The extents of the Mimbres Basin are approximately:

Longitude:	107° 30' N - 108° 0' N	(50 km)
Latitude:	32° 0' N - 32° 30' N	(50 km)



4. Socio-economic effects of subsidence

Unknown.

5. Customer / contact

Charles E. Heywood, U.S. Geological Survey, Albuquerque, NM,
E-mail: cheywood@usgs.gov

Randy Hanson, Hydrologist, California District, Water Resources Division, U.S. Geological Survey,
E-mail: rthanson@usgs.gov

6. Subsidence rate/amount *Rating: Low*

A subsidence rate of around 1 cm/year has been ongoing for the period 1953-1990.

7. Ground-truth available *Rating: Good*

Extensive ground-truth data available including a groundwater hydrology model.

8. Land cover *Rating: Good*

Arid to semi-arid environment with areas of irrigated agriculture and small scattered settlements.

9. ERS data availability and status *Rating: Medium*

No suitable ascending pairs.
10 Descending: pairs with perpendicular baselines less than 50m and a temporal separation greater than a year.

Receiving Station: Prince Albert

10. DEM availability

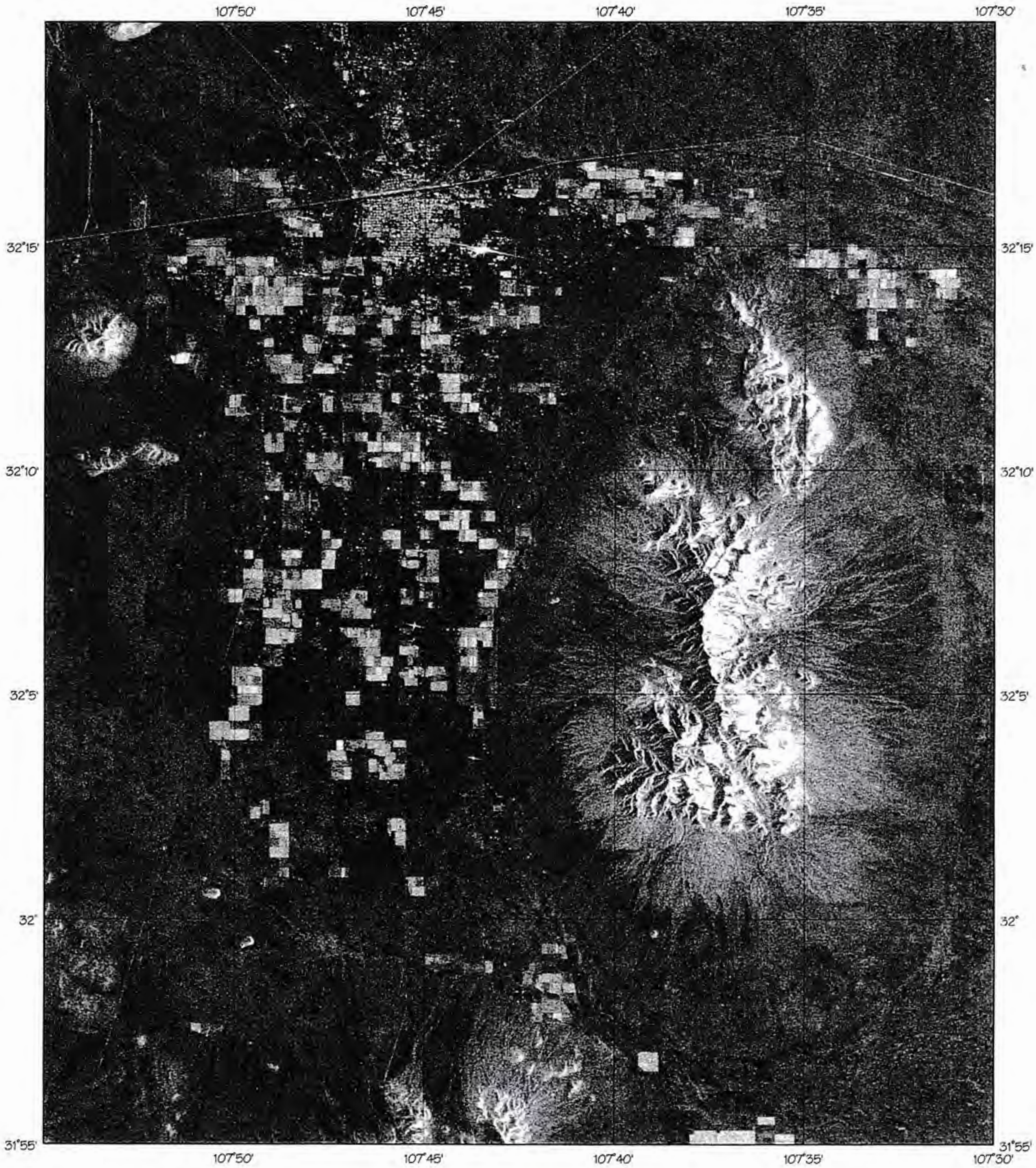
- USGS 1 arc second resolution xy and 20m z DEM available in 0.5° × 0.5° tiles.
  Cost approx. $100 for first tile, additional tiles much cheaper.
- USGS 3 arc second resolution xy and 20m z DEM for the whole of the US held in-house.
- GTOPO-30 coarse 1km resolution DEM of variable quality held in-house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in-house yet.
- Tandem InSAR.

11. Processing status

Differential interferogram produced.

Radar amplitude image for the Mimbres Basin, New Mexico

ERS scene date: 12 November 1995



0 5 10 15 20 25 km

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SAR & InSAR Processing Summary Report | **Mimbres Basin, New Mexico: MIM_1 & MIM_2**

1. Image Acquisition Dates:	12/11/95, 17/11/97
2. Temporal Separation:	2 years
3. Processing Stage (1[int], 2[diff] or 3[full]):	2
4. DEM details, if used:	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. SLC Processing:	
(i) Scene centre lat/long:	32° 11' 46" N, 107° 29' 39"W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	32° 12' 01" N,107° 32' 44" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	97.1 km × 107.1 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	38 m
(b) Derived from Precise State Vectors:	40.54 m
(iii) Altitude of Ambiguity:	232.26 m
(iv) Range × Azimuth extents:	97.4 km × 107.1 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	17.83
(ii) Standard Deviation:	13.76

9. Analysis/Interpretation of Results

The quality of this differential interferogram is generally good, with no significant atmospheric or other artefacts, and with good coherence over non-cultivated areas.

At first sight there is little obvious evidence of subsidence. However, the town of Deming does have a distinct 'border' in the interferogram, suggesting that some subsidence over the township is occurring. It is however difficult to assess the magnitude of the subsidence in view of the poor coherence over this cultivated area.

10. Conclusions/Recommendations

Category	Label	Co-ordinates	Comments
1 class C feature	C1	32° 07' N 107° 47' W	Probable subsidence over Deming

Categories: **A** *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/Feature of interest*

It would be worthwhile obtaining acquisitions with a shorter temporal interval.

El Paso, Texas — OVERALL RATING: 53%

1. Marketability — Rating: Medium

El Paso relies on groundwater to meet the bulk of its demand for water in an arid environment. It has a long history of subsidence and demand for water is growing.

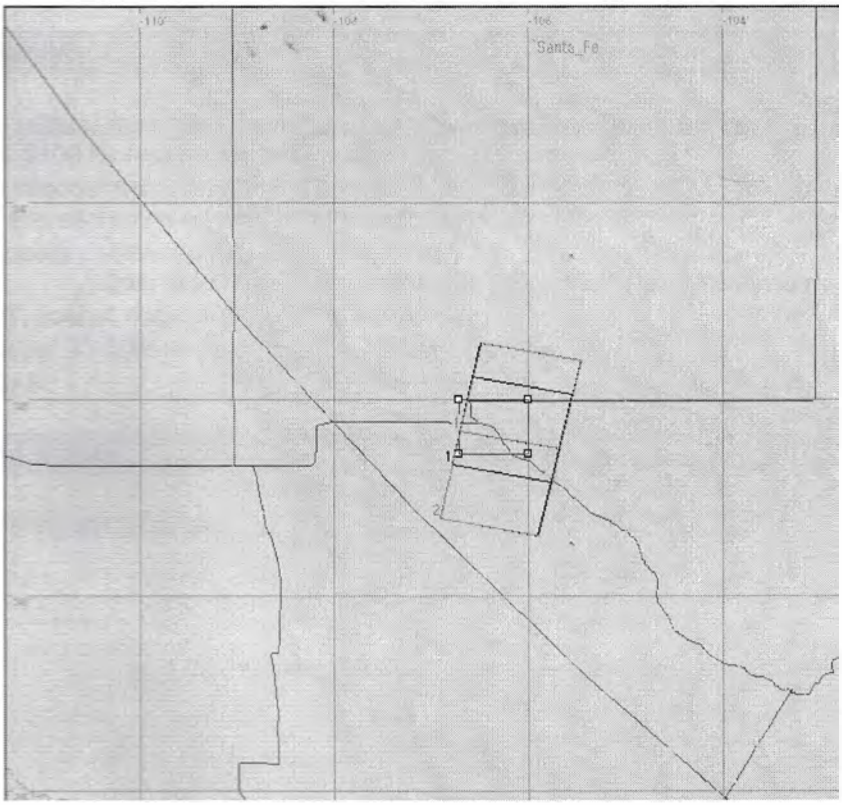
2. Subsidence category

Groundwater abstraction.

3. Geographical extents and optimal ERS coverage

The extents of the El Paso area are approximately:

Longitude:	106° 0' W -106° 43' W	(50 km)
Latitude:	31° 27' N - 32° 0' N	(40 km)



4. Socio-economic effects of subsidence

Unknown.

5. Customer / contact

Charles E. Heywood, U.S. Geological Survey, Albuquerque, NM, E-mail: cheywood@usgs.gov

6. Subsidence rate/amount — Rating: Low

Current rate of subsidence unknown.

7. Ground-truth available — Rating: Poor

None currently available.

8. Land cover — Rating: Medium

Medium sized urban area in an arid environment.

9. ERS data availability and status — Rating: Medium

No suitable ascending pairs.

Descending: 12 pairs with perpendicular baselines less than 50m and a temporal separation greater than a year.

Receiving Station: Prince Albert

10. DEM availability

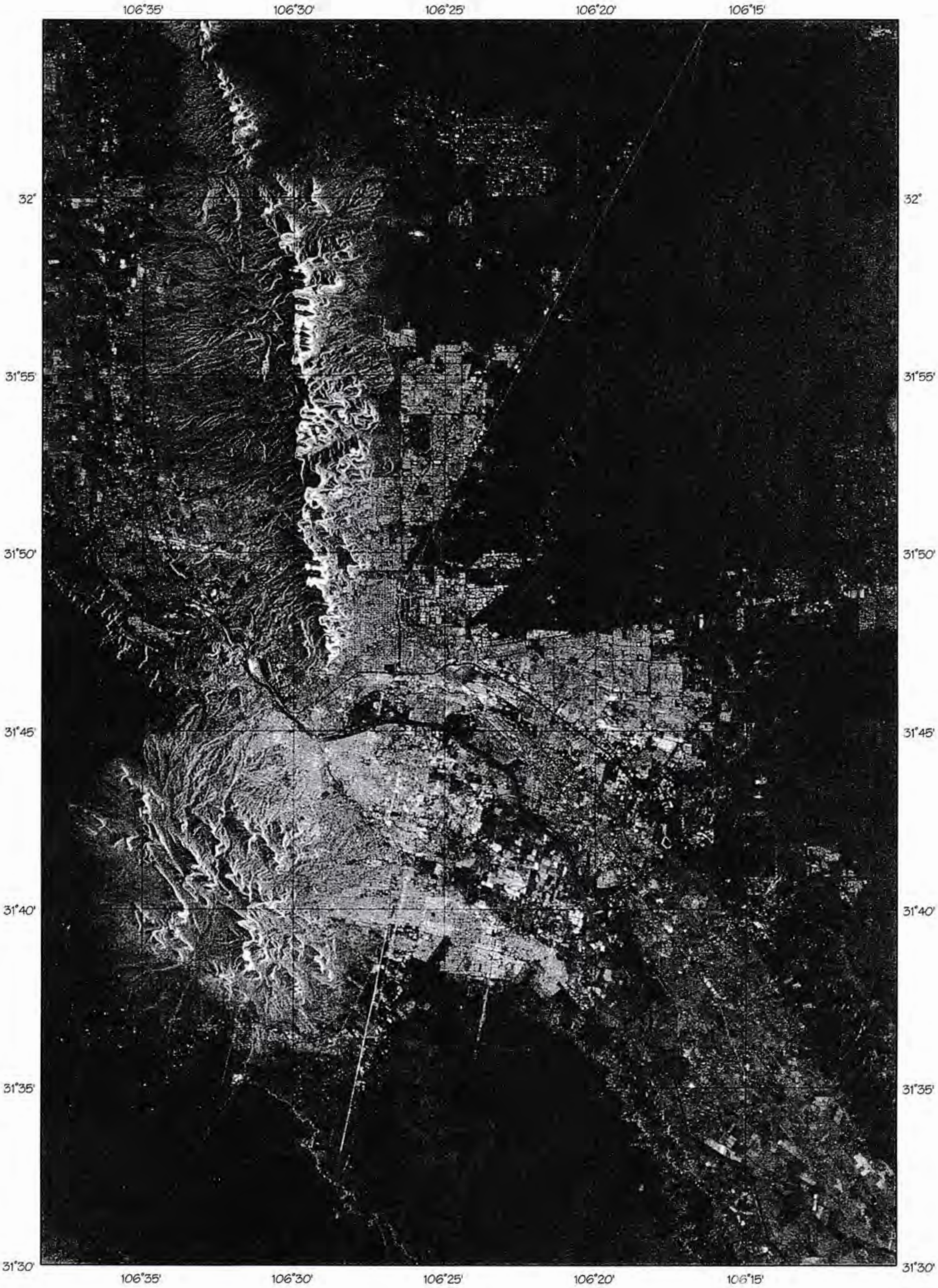
- USGS 1 arc second resolution xy and 20m z DEM available in 0.5° × 0.5° tiles.
  Cost approx. $100 for first tile, additional tiles much cheaper.
- USGS 3 arc second resolution xy and 20m z DEM for the whole of the US held in-house.
- GTOPO-30 coarse 1km resolution DEM of variable quality held in-house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in-house yet.
- Tandem InSAR.

11. Processing status

Differential interferogram produced.

Radar amplitude image for the El Paso, Texas area

ERS scene date: 15 December 1995



0 5 10 15 20 25 km

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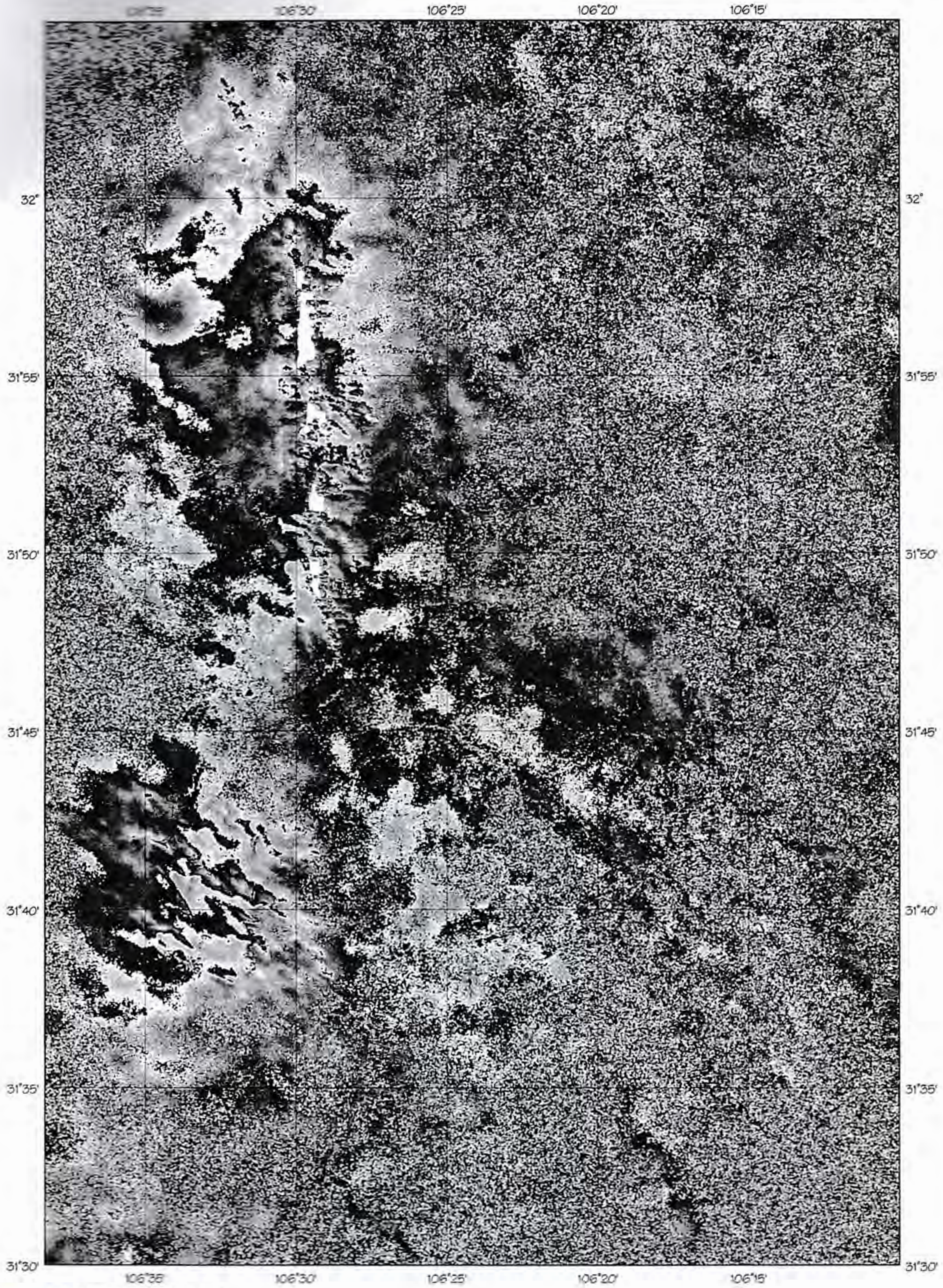
Differential interferogram for the El Paso, Texas area

ERS scene dates: [illegible] 1997
Temporal separation: [illegible]
Perpendicular baseline: [illegible] m
Altitude of ambiguity: [illegible] m



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SAR & InSAR Processing Summary Report **El Paso, Texas: ELP_1 & ELP_2**

1. **Image Acquisition Dates:**	15/12/95, 10/10/97
2. **Temporal Separation:**	1 year 10 months
3. **Processing Stage (1[int], 2[diff] or 3[full]):**	2
4. **DEM details, if used:**	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. **SLC Processing:**	
(i) Scene centre lat/long:	31° 42' 04" N, 106° 10' 52°W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. **Ground-range PRI (Amplitude Image) Processing:**	
(i) Scene centre lat/long:	31° 42' 20" N,106° 13' 56" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	96.3 km × 107.1 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. **InSAR Processing**	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	29 m
(b) Derived from Precise State Vectors:	26.1 m
(iii) Altitude of Ambiguity:	360.8 m
(iv) Range × Azimuth extents:	97.7 km × 107.1 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. **Coherence Map Parameters**	
(i) Mean:	22.02
(ii) Standard Deviation:	17.37

9. Analysis/Interpretation of Results

This differential interferogram is of disappointing quality, with pronounced phase 'mottling' evident over the regions of high coherence. The phase noise is presumed to arise from atmospheric effects.

10. Conclusions/Recommendations

The magnitude of the phase noise and its spatial characteristics are such that it is only possible to conclude that there are no regions of substantial subsidence within the scene over this temporal interval.

Houston, Texas — OVERALL RATING: 73%

1. Marketability — *Rating: Good*

Consultation with Tom Michel of the Harris-Galveston Coastal Subsidence District had revealed that there are no mechanisms to reduce the problem at present and that any solution is not likely to occur until 2010 to 2015. Since processing one interferogram over Houston, NPA has secured a contract from the above agency to carry out further InSAR processing over Houston.

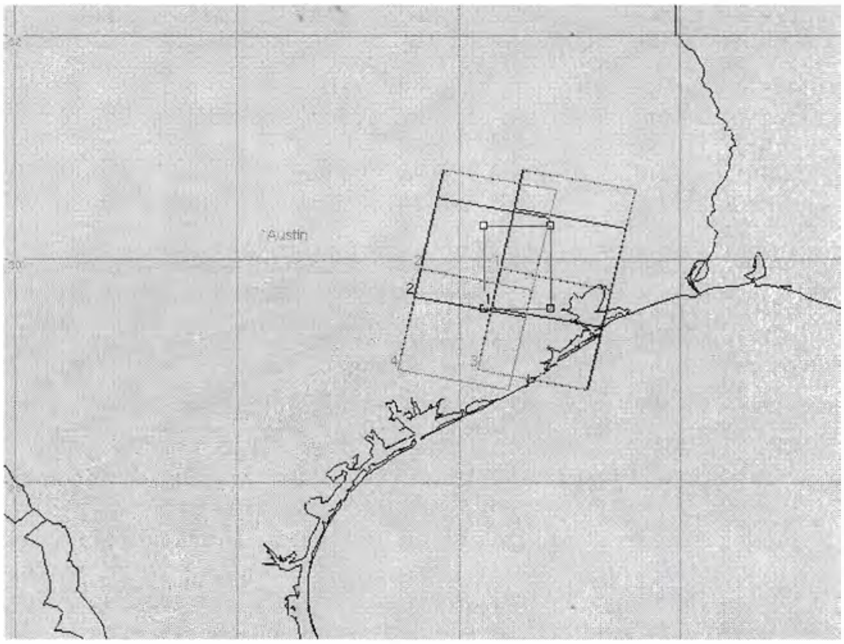
2. Subsidence category

Groundwater extraction.

3. Geographical extents and optimal ERS coverage

The extents of recorded subsidence in the Houston/Galveston area are approximately:

Longitude:	95° 10' W - 95° 46' W	(50 km)
Latitude:	29° 33' N - 30° 18' N	(80 km)



4. Socio-economic effects of subsidence

Annual costs of subsidence mitigation in selected areas where such figures are estimated are more than $30 million a year for the Houston-Galveston area. The Houston ship canal has seen more than 10 feet of subsidence and many of the industrial facilities in the vicinity have had to be repaired. The Johnson Space Centre (in the southeastern part of Houston) has also been threatened by subsidence.

5. Customer / contact

Don Helm, Nevada Bureau of Mines and Geology, University of Nevada-Reno,
E-mail: helm@eng.morgan.edu

Tom Michel, Harris-Galveston Coastal Subsidence District, Friendswood, Texas,
E-mail: tmichel@HGCSD.DST.TX.US

6. Subsidence rate/amount *Rating: Medium*

8-10 feet of subsidence has occurred between 1906-1987.
An annual rate of between 0.1 to 0.2 feet has been recorded in the period 1987 to 1995.

7. Ground-truth available *Rating: Good*

Extensive GPS and extensometer networks are in place; charts of subsidence for the period 1987 to 1995 are available.

8. Land cover *Rating: Medium*

Major urban area, surrounded by areas of humid vegetation.

9. ERS Data availability and status *Rating: Low*

No suitable ascending frames are available.
Descending frames:

1. Western (most suitable) track: 80% of specified area covered: 6 pairs with perpendicular baselines less than 50m and a temporal separation greater than a year. However a number of scenes contained missing lines.
2. Eastern track: 80% of specified area covered: 9 pairs with perpendicular baselines less than 50m and a temporal separation greater than a year.

Receiving Station: Gatineau

10. DEM Availability

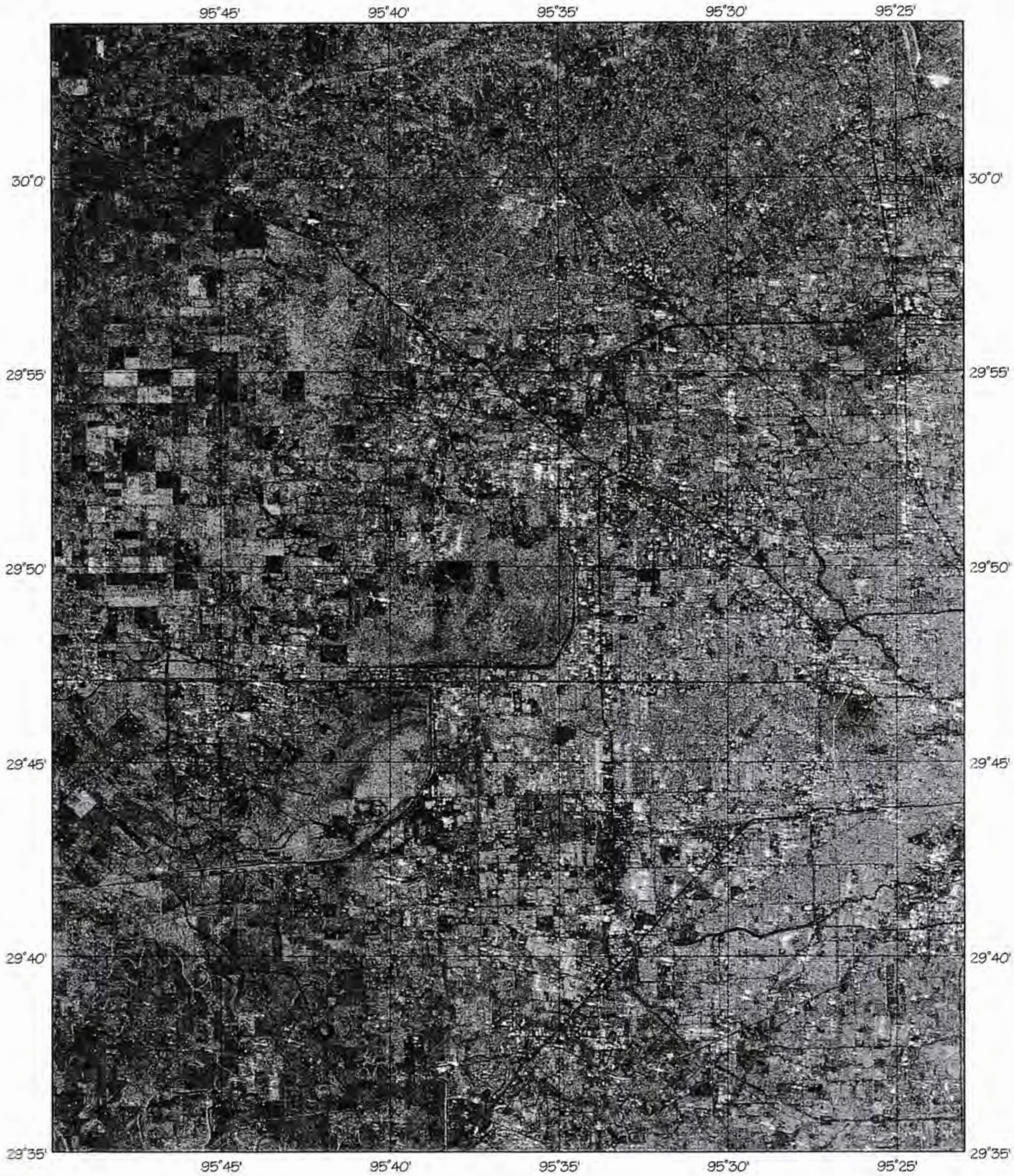
- USGS 1 arc second resolution xy and 20m z DEM available in 0.5° × 0.5° tiles.
  Cost approx. $100 for first tile, additional tiles much cheaper.
- USGS 3 arc second resolution xy and 20m z DEM for the whole of the US held in-house.
- GTOPO-30 coarse 1km resolution DEM of variable quality held in-house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in-house yet.
- Tandem InSAR.

11. Processing Status

Differential interferogram produced.

Radar amplitude image for the Jersey Village area, Houston

ERS scene date: 17 February 1996



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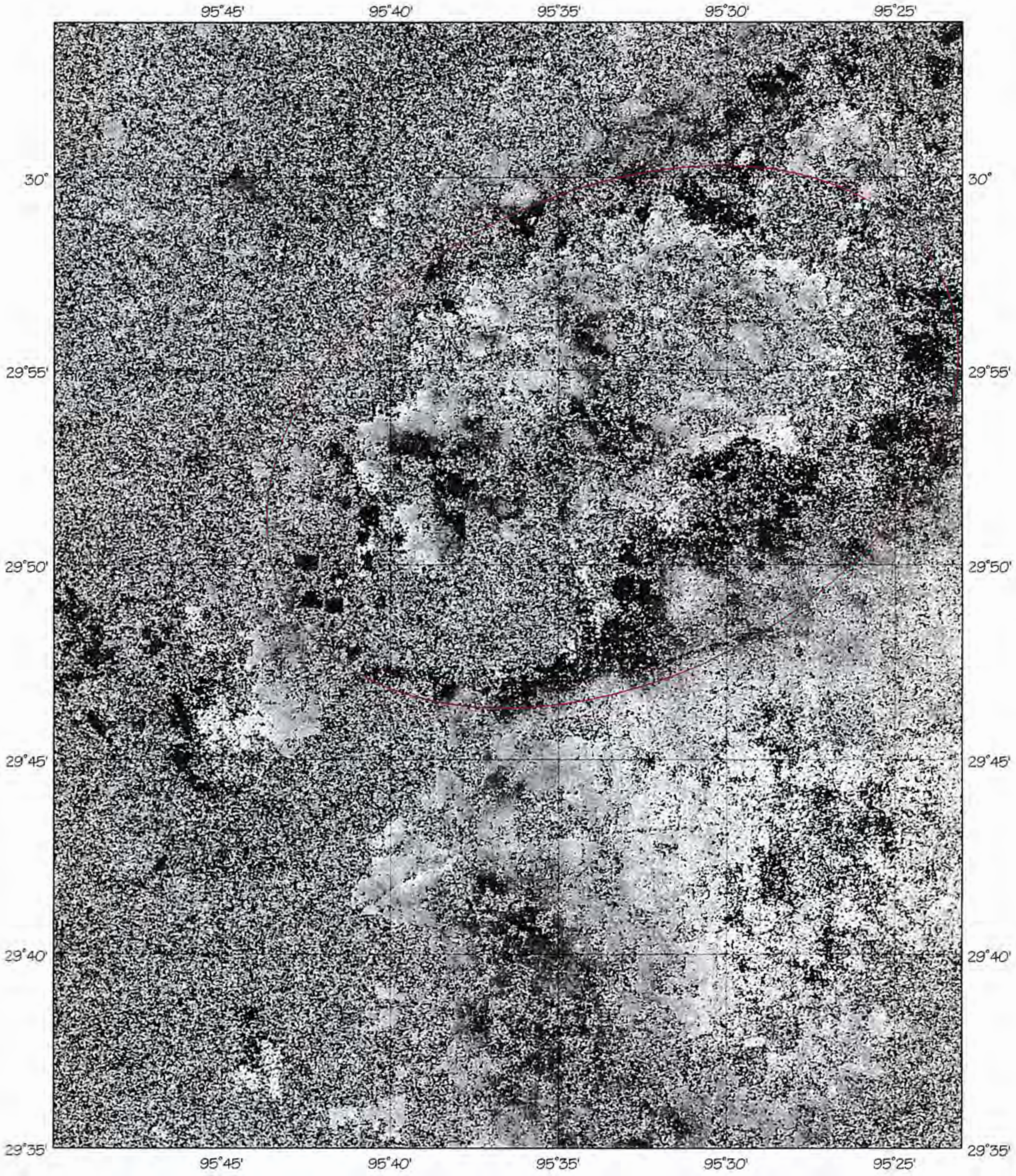
Differential interferogram for the Jersey Village area, Houston

ERS scene dates: 17 February 1996 & 13 April 1997
Temporal separation: 1 year 2 months
Perpendicular baseline: 93.4 m
Altitude of ambiguity: 100.8 m

Rings indicate fringe features in this image



0 5 10 15 20 km

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SAR & InSAR Processing Summary Report	**Houston: HOU_3 & HOU_4**

1. **Image Acquisition Dates:**	17/2/96, 13/4/97
2. **Temporal Separation:**	1 year 2 months
3. **Processing Stage (1[int], 2[diff] or 3[full]):**	3
4. **DEM details, if used:**	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. **SLC Processing:**	
(i) Scene centre lat/long:	29° 58' 05" N, 95° 48' 50"W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. **Ground-range PRI (Amplitude Image) Processing:**	
(i) Scene centre lat/long:	29° 57' 37" N 95° 49' 34" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	97.2 km × 104.9 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. **InSAR Processing**	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	89 m
(b) Derived from Precise State Vectors:	93.43 m
(iii) Altitude of Ambiguity:	100.78 m
(iv) Range × Azimuth extents:	99.5 km × 106.6 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. **Coherence Map Parameters**	
(i) Mean:	22.47
(ii) Standard Deviation:	13.19

9. Analysis/Interpretation of Results

The Jersey village suburb of Houston and the surrounding region is known to be subsiding. Ground based extensometer measurements have assessed the subsidence as consistent over the last 20 years, and with a peak rate in excess of 3cm/year. This site was consequently of some interest, to see whether the interferometric phase variations were consistent with ground based measurements.

The SAR data has been corrected for the effects of topography using a 100m digital elevation model, and the geo-referencing given by the lat/long grid is accurate to approx. 100m.

The coherence levels are good only over the urban environment, and localised regions of low coherence disrupt the interferometric subsidence pattern. Despite the regions of low coherence a consistent subsidence pattern can be readily identified by eye, with a focus at 95° 33' W, 29° 53' N, with a maximum relative displacement of order 6 cm over the 14 month interval. The interferometric subsidence field is extensive, with typically 3 cm of displacement over a region of 20 km by 10 km, and wholly consistent with the available ground truth.

10. Conclusions/Recommendations

Category	Label	Grid ref.	Comments
A	A1	95° 33' W 29° 53' N	Wide scale subsidence of a magnitude >3 cm/year.

Categories: A *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/Feature of interest*

The temporal separation between these acquisitions is small in the context of the subsidence rates and the geographical scale of the subsidence field. It would be very worthwhile to process a further pair of acquisitions with a 3 or 4 year separation, if suitable data is available, possibly with a view to construction of a high resolution subsidence map for the Jersey Village area.

Bingham Canyon and Salt Lake City, Utah

OVERALL RATING: 60%

1. Marketability — *Rating: Medium*

Bingham Canyon is the largest open cast mine in the world. Dr. Callender, of Kennecott Corp. who operate the mine, expressed great interest in the application of interferometry in detecting earth movements associated with the mining activity.

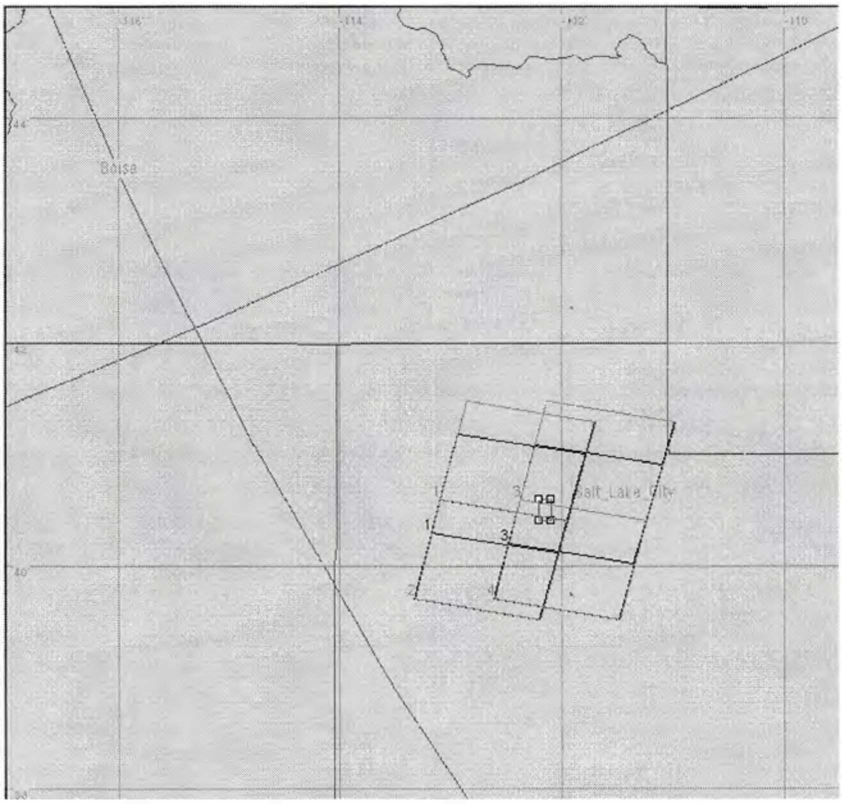
2. Subsidence category

Mineral extraction, and groundwater withdrawals at the Bingham Canyon mine, with associated micro seismic events.
Possible groundwater extraction problems in Salt Lake City.

3. Geographical extents and optimal ERS coverage

The extents of the Bingham Canyon area are approximately:

Longitude:	112° 5' W - 112° 11' W	(10 km)
Latitude:	40° 24' N - 40° 35' N	(15 km)



4. Socio-economic effects of subsidence

Unknown.

5. Customer / contact

Jon Callender, Kennecott Corp. E-mail: kjallen@kennecott.com

Jon Cherry, Kennecott Corp. E-mail: cherryj@kennecott.com

Robert L Baskin, Hydrologist, U. S. Geological Survey, Salt Lake City, E-mail: rbaskin@usgs.gov

6. Subsidence rate/amount — *Rating: Low*

Unknown.

7. Ground-truth available — *Rating: Poor*

None currently available.

8. Land cover — *Rating: Medium*

Bingham Canyon is surrounded by forested, mountainous land, while Salt Lake City is a large city.

9. ERS data availability and status — *Rating: High*

No suitable ascending pairs.
Descending:

1. Western track: 8 pairs with perpendicular baselines less than 50m and a temporal separation greater than a year.

2. Eastern track (includes Salt Lake City): 15 pairs with perpendicular baselines less than 50m and a temporal separation greater than a year.

Receiving Station: Prince Albert

10. DEM availability

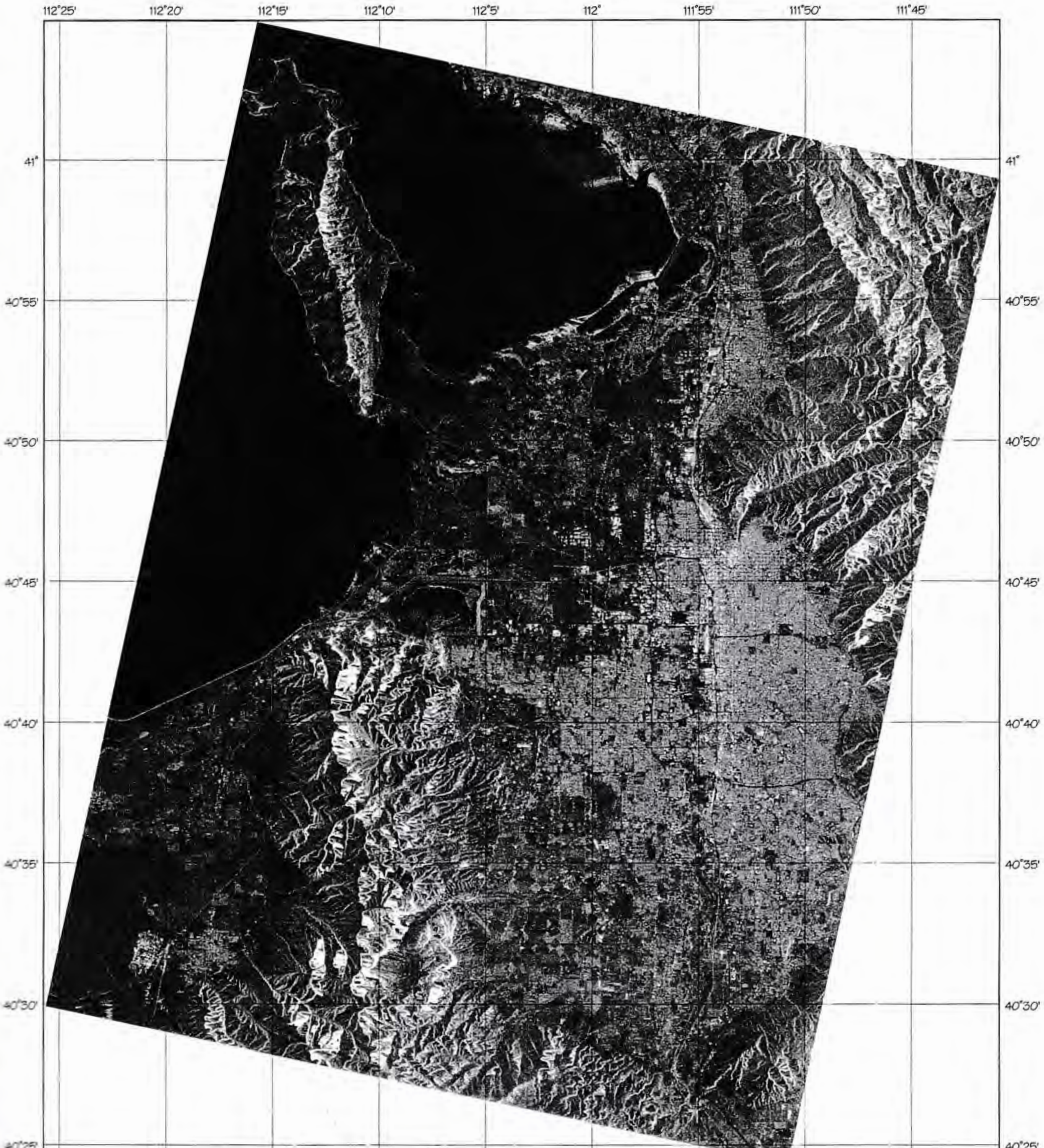
- USGS 1 arc second resolution xy and 20m z DEM available in 0.5° × 0.5° tiles.
  Cost approx. $100 for first tile, additional tiles much cheaper.
- USGS 3 arc second resolution xy and 20m z DEM for the whole of the US held in-house.
- GTOPO-30 coarse 1km resolution DEM of variable quality held in-house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in-house yet.
- Tandem InSAR.

11. Processing status

Two differential interferograms produced.

Radar amplitude image for the Bingham Canyon and Salt Lake City, Utah area

ERS scene date: 21 September 1992



0 5 10 15 20 25 km

NPA SATELLITE MAPPING

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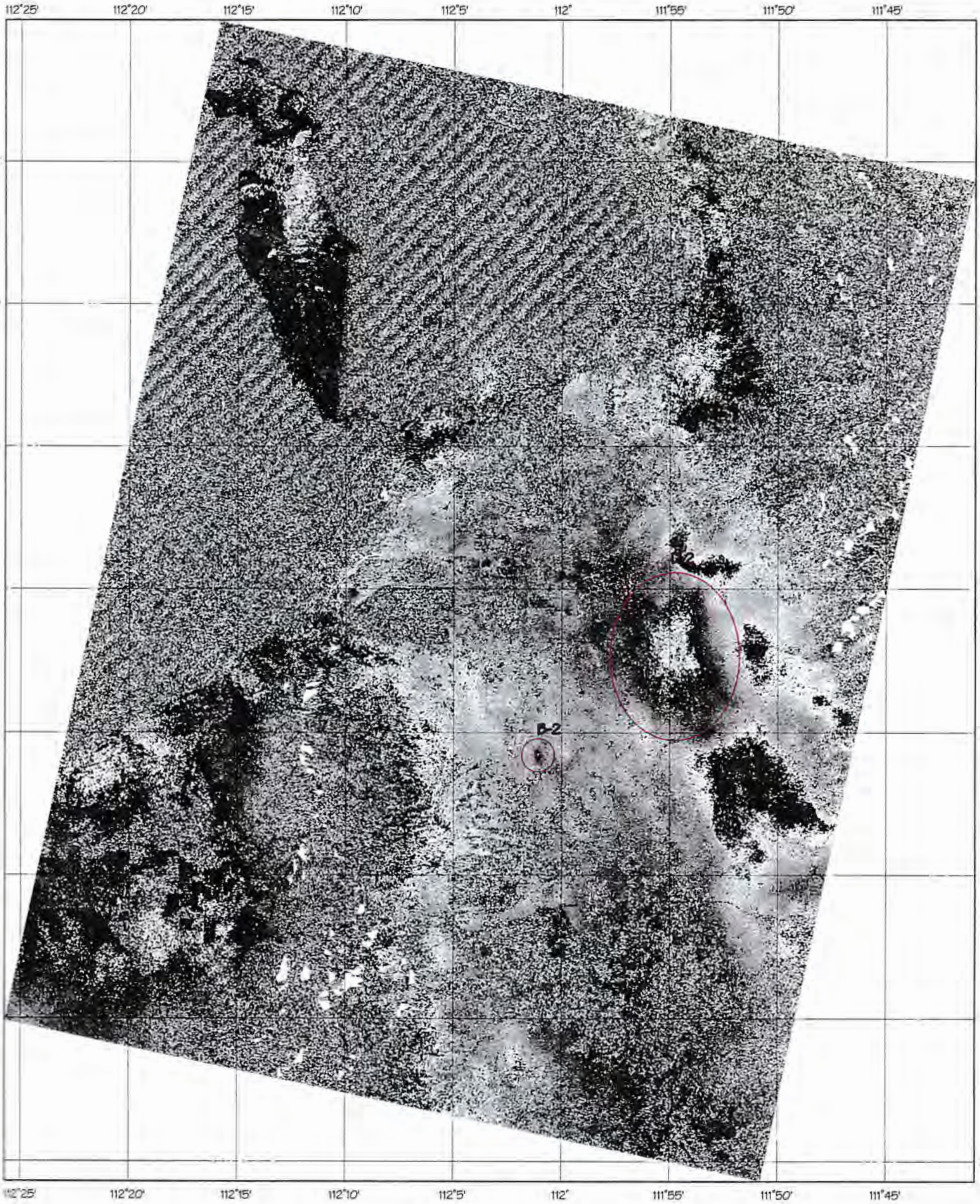
Differential interferogram for the Bingham Canyon and Salt Lake City, Utah area

ERS scene dates: 21 September 1992 & 11 October 1993
Temporal separation: 1 year 1 month
Perpendicular baseline: 15.6 m
Altitude of ambiguity: 603.6 m

Rings indicate fringe features in this image



NPA SATELLITE MAPPING

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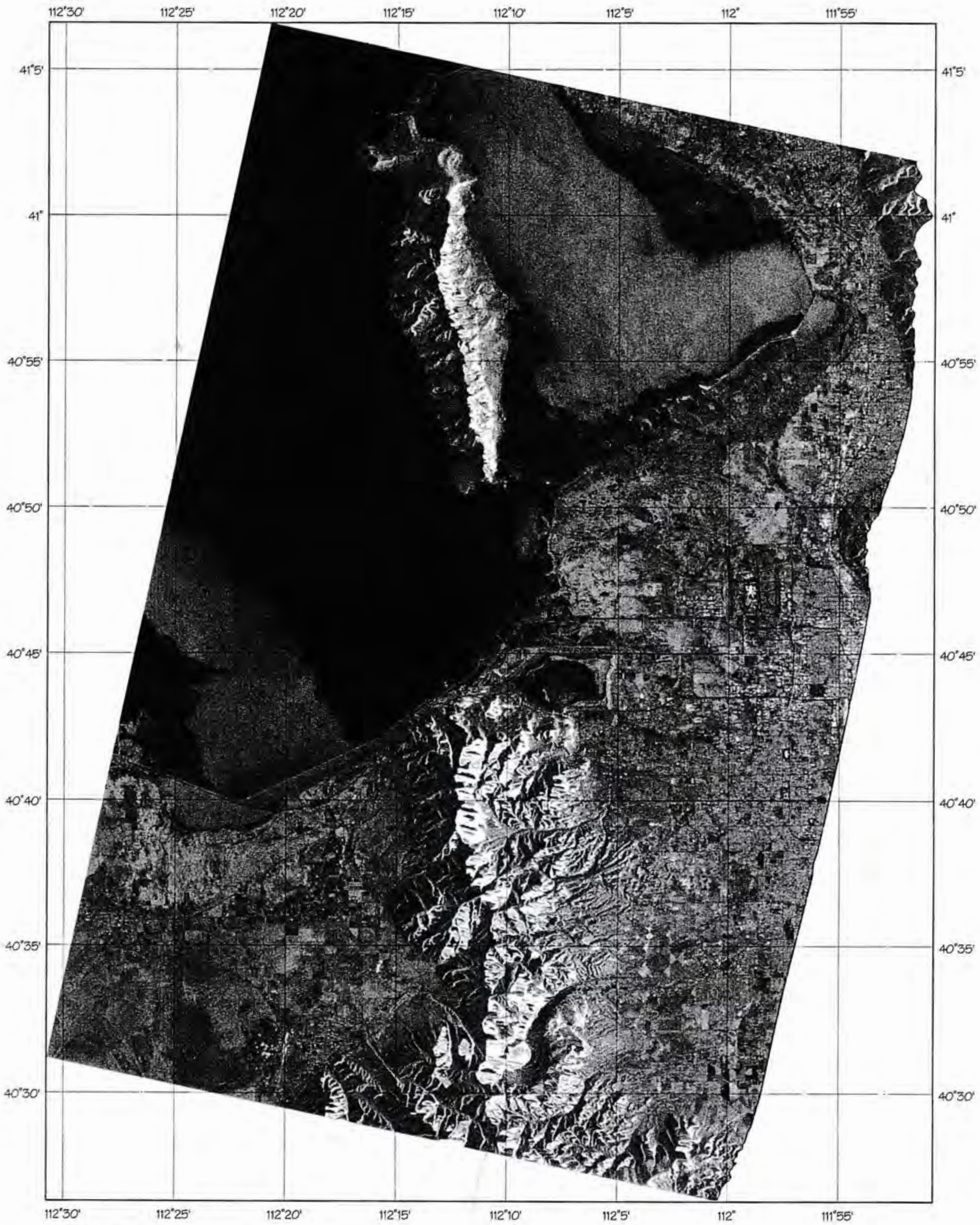
Radar amplitude image for the Bingham Canyon and Salt Lake City, Utah area

ERS scene date: 5 June 1995



0 5 10 15 20 25 km

NPA SATELLITE MAPPING

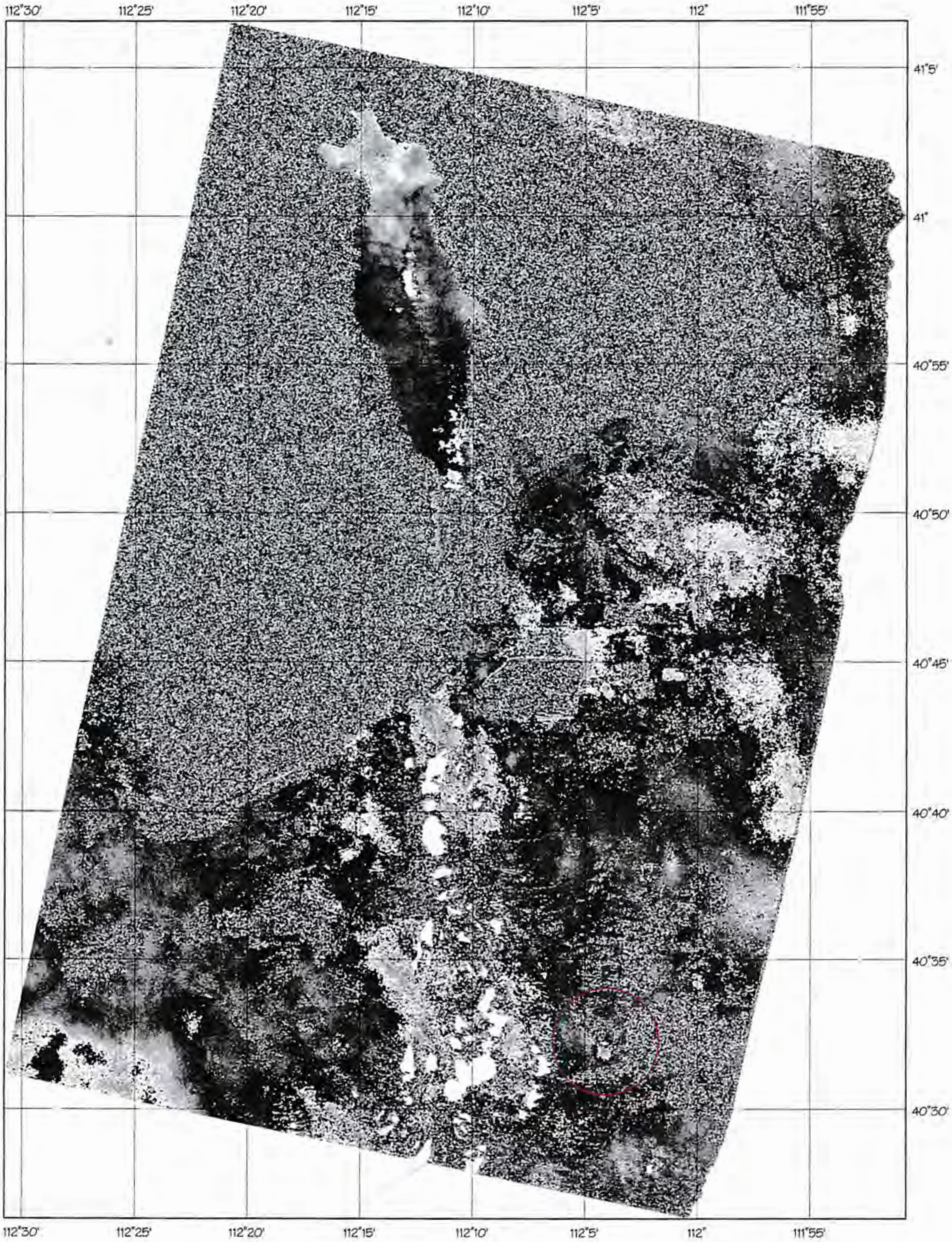
esa european space agency

Supported by DERA PHOENIX

Differential interferogram for the Bingham Canyon and Salt Lake City, Utah area

ERS scene dates: 5 June 1995 & 21 May 1996
Temporal separation: 11 months
Perpendicular baseline: 16.0 m
Altitude of ambiguity: 588.5 m

Rings indicate fringe features in this image



0 5 10 15 20 25 km

NPA SATELLITE MAPPING

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SAR & InSAR Processing Summary Report	**Bingham Canyon and Salt Lake City, Utah: BIN_1 & BIN_2**

1. Image Acquisition Dates:	21/9/92 , 11/10/93
2. Temporal Separation:	1 year 1 month
3. Processing Stage (1[int], 2[diff] or 3[full]):	2
4. DEM details, if used:	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. SLC Processing:	
(i) Scene centre lat/long:	40° 34' 12"N, 111° 39' 25"W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	40° 34' 35" N,111° 51' 22" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	95.0 km × 107.0 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	11 m
(b) Derived from Precise State Vectors:	15.6 m
(iii) Altitude of Ambiguity:	603.6 m
(iv) Range × Azimuth extents:	96.0 km × 104.8 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	16.52
(ii) Standard Deviation:	14.61

9. Analysis/Interpretation of Results

These two scenes are on separate tracks and the two interferograms only overlap by about 50% in longitude.

The coherence levels for both interferograms are generally good, but unfortunately both scenes also exhibit a considerable degree of random phase variation, ascribed to atmospheric effects. Interpretation is consequently difficult, and has been limited to the overlap region.

Two small (1 km diameter) localised regions of subsidence can be seen in the metropolitan area of Salt Lake City on both interferograms, with subsidence rates at around 2-3 cm/year. Aside from these locations, no consistent larger scale regions of subsidence have been identified. The feature D2, for example, appears only on the first interferogram, and is almost certainly an atmospheric phase artefact.

The phase 'waves' in the salt lake (D1) are a coherent noise artefact, almost certainly arising from a residual DC bias. The radar return from the salt lake is extremely low, at a level comparable to the thermal noise, with the consequence that the DC bias is the predominant signal component. The observed phase variation corresponds to the expected interferometric phase variation of the ellipsoidal earth surface, which has been subtracted from the data.

10. Conclusions/Recommendations

Category	Label	Co-ordinates	Comments
2 class B features	B1	112° 4' W 40° 32' N	Localised subsidence <2 cm/year
	B2	112° 1' W 40° 39' N	Localised subsidence <3 cm/year
2 class D features	D1	112° 5' W 40° 55' N	Coherent noise artefact in image of salt lake
	D2	111° 55' W 40° 43' N	Atmospheric noise artefact

Categories: **A** *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/Feature of interest*

SAR & InSAR Processing Summary Report	**Bingham Canyon and Salt Lake City, Utah: BIN_3 & BIN_4**

1. Image Acquisition Dates:	5/6/95, 21/5/96
2. Temporal Separation:	11 months
3. Processing Stage (1[int], 2[diff] or 3[full]):	2
4. DEM details, if used:	
(i) Type:	ER Mapper USA DEMs
(ii) Pixel size:	3 arc seconds
(iii) Accuracy – Planimetric & Vertical:	15 m (vertical)
5. SLC Processing:	
(i) Scene centre lat/long:	40° 38' 31"N, 112° 28' 59"W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	40° 38' 54" N,112° 33' 12" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	96.5 km × 106.9 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	16 m
(b) Derived from Precise State Vectors:	16.0 m
(iii) Altitude of Ambiguity:	588.5 m
(iv) Range × Azimuth extents:	96.7 km × 106.7 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	22.99
(ii) Standard Deviation:	17.61

9. Analysis/Interpretation of Results

These two scenes are on separate tracks and the two interferograms only overlap by about 50% in longitude.

The coherence levels for both interferograms are generally good, but unfortunately both scenes also exhibit a considerable degree of random phase variation, ascribed to atmospheric effects. Interpretation is consequently difficult, and has been limited to the overlap region.

Two small (1 km diameter) localised regions of subsidence can be seen in the metropolitan area of Salt Lake City on both interferograms, with subsidence rates at around 2-3 cm/year. Aside from these locations, no consistent larger scale regions of subsidence have been identified. The feature D2, for example, appears only on the first interferogram, and is almost certainly an atmospheric phase artefact.

The phase 'waves' in the salt lake (D1) are a coherent noise artefact, almost certainly arising from a residual DC bias. The radar return from the salt lake is extremely low, at a level comparable to the thermal noise, with the consequence that the DC bias is the predominant signal component. The observed phase variation corresponds to the expected interferometric phase variation of the ellipsoidal earth surface, which has been subtracted from the data.

10. Conclusions/Recommendations

Category	Label	Co-ordinates	Comments
2 class B features	B1	112° 4' W 40° 32' N	Localised subsidence <2 cm/year
	B2	112° 1' W 40° 39' N	Localised subsidence <3 cm/year
2 class D features	D1	112° 5' W 40° 55' N	Coherent noise artefact in image of salt lake
	D2	111° 55' W 40° 43' N	Atmospheric noise artefact

Categories: A *Definite, large-scale subsidence*

B *Probable/smaller-scale subsidence over a larger area*

C *Possible subsidence over a larger area*

D *Processing artefact/ Feature of interest*

Mexico City — OVERALL RATING: 60%

1. Marketability — *Rating: Medium*

Mexico City is historically a famous site of subsidence where subsidence has reached as much as 9m locally. A good contact has been established and he is interested in collaborating with NPA on further studies of the subsidence in Mexico City using interferometry.

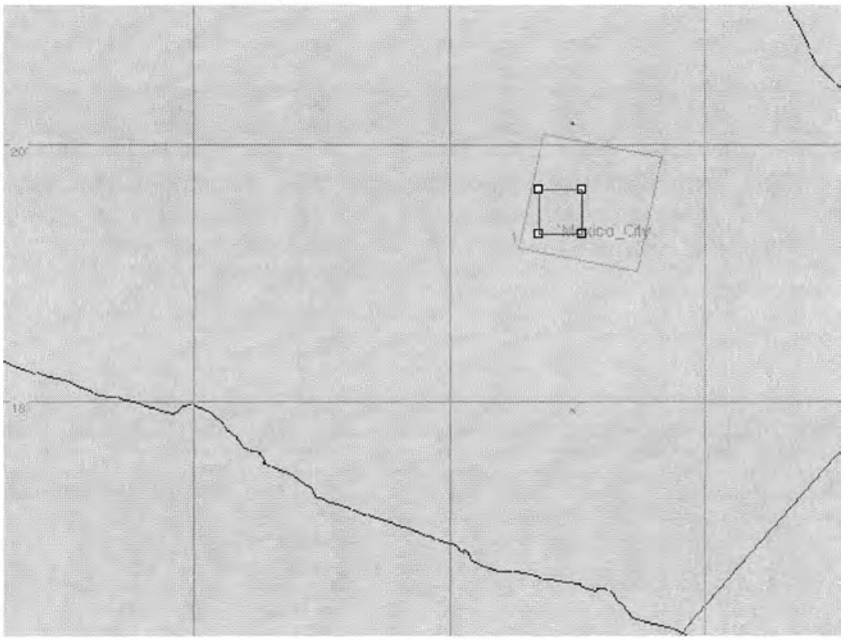
2. Subsidence category

Groundwater extraction.

3. Geographical extents and optimal ERS coverage

The extents of Mexico City are approximately:

Longitude:	98° 58' W - 99° 18' W	(45 km)
Latitude:	19° 18' N - 19° 39' N	(45 km)



4. Socio-economic effects of subsidence

No details of the socio-economic effects of the subsidence are known.

5. Customer / contact

Prof. Cinna Lomnitz, Instituto de Geofisica, UNAM, Mexico, E-mail: cinna@ollin.igeofcu.unam.mx

Don Helm, Nevada Bureau of Mines and Geology, University of Nevada-Reno,
E-mail: helm@eng.morgan.edu

6. Subsidence rate/amount — *Rating: Medium*

Since 1959 an average of 5 to 6 cm of subsidence a year has been observed. Subsidence as high as 50 cm a year has been known in some areas

7. Ground-truth available — *Rating: Poor*

Information on current ground truth is unknown, but there are proposals to use GPS to monitor the subsidence.

8. Land cover — *Rating: Good*

Large urban area surrounded by mountainous regions.

9. ERS Data availability and status — *Rating: Low*

No suitable ascending pairs available.
No descending pairs with perpendicular baselines less than 50 m and a temporal separation of greater than 1 year.
Alternatives are a pair with a temporal separation of 5-months and a perpendicular baseline of 26 m, or a 1 year 3 month separation pair with a perpendicular baseline of 70m.

Receiving Station: Norman

10. DEM availability

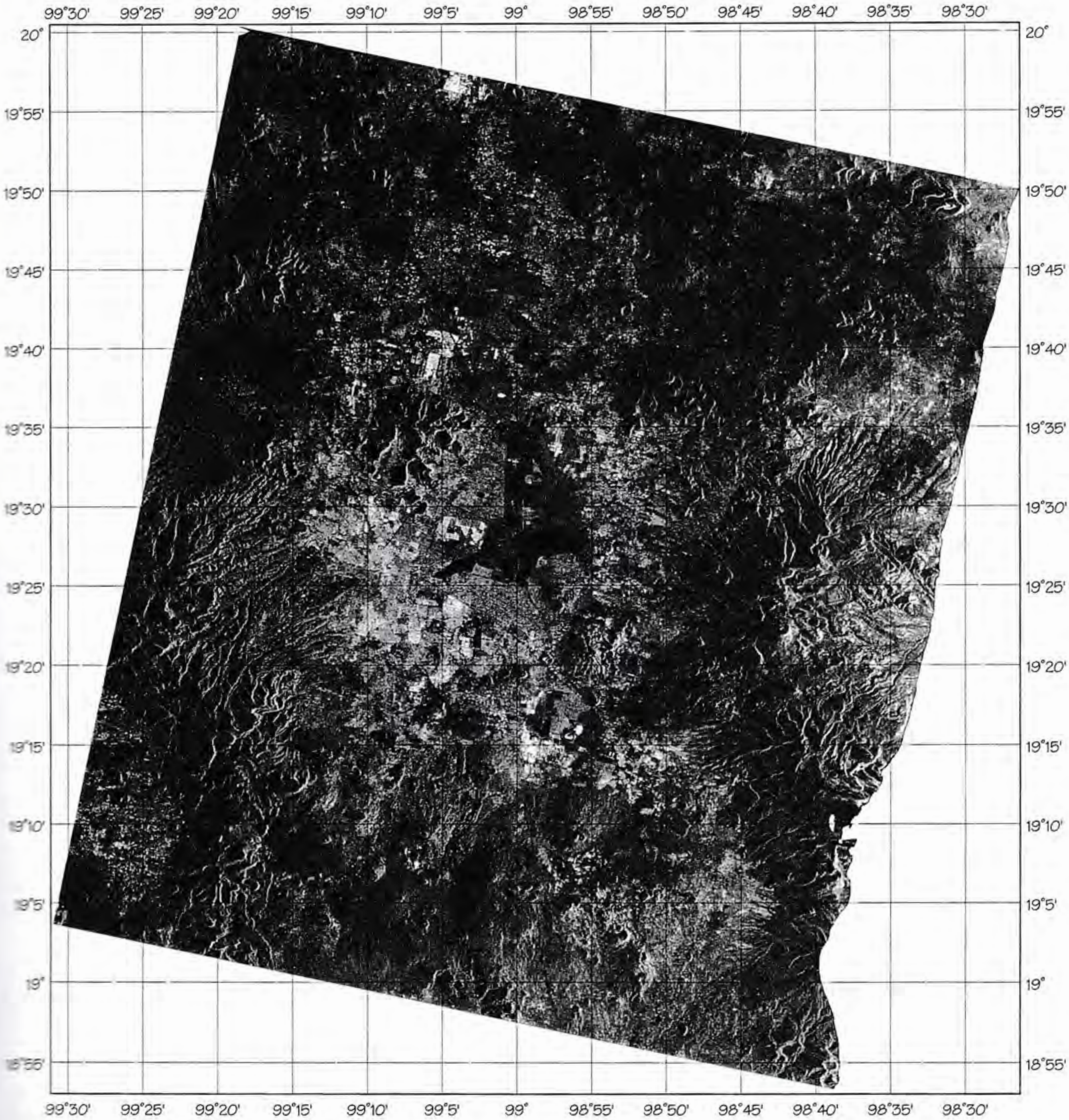
- GTOPO-30 coarse 1km resolution DEM of variable quality held in-house.
- Russian Mapping, 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in-house yet.
- Tandem InSAR.

11. Processing status

Differential Interferogram produced.

Radar amplitude image for the Mexico City area

ERS scene date: 21 June 1996



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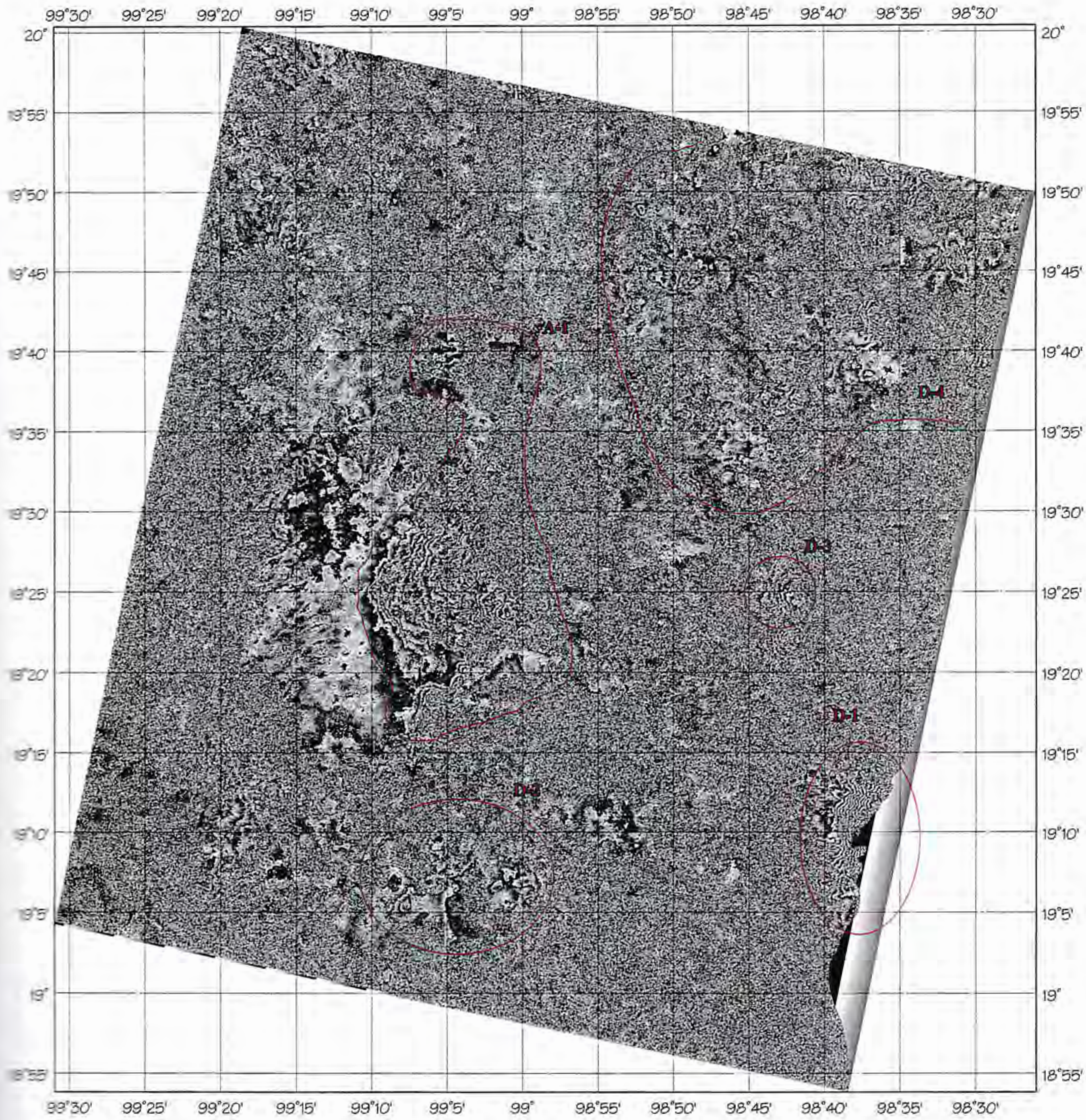
Differential interferogram for the Mexico City area

ERS scene dates: 21 June 1996 & 19 September 1997
Temporal separation: 1 year 3 months
Perpendicular baseline: 66.6 m
Altitude of ambiguity: 141.4 m

Rings indicate fringe features in this image



0 10 20 30 40 50 km

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SAR & InSAR Processing Summary Report **Mexico City : MEX_1 & MEX_2**

1. **Image Acquisition Dates:**	21/6/96, 19/9/97
2. **Temporal Separation:**	1 year 3 months
3. **Processing Stage (1[int], 2[diff] or 3[full]):**	2
4. **DEM details, if used:**	
(i) Type:	GTOPO-30
(ii) Pixel size:	1 km
(iii) Accuracy – Planimetric & Vertical:	variable
5. **SLC Processing:**	
(i) Scene centre lat/long:	19° 26' 28" N, 98° 56' 28"W
(ii) Full- (or sub-) scene Range × Azimuth extents:	99.3 km × 107.0 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. **Ground-range PRI (Amplitude Image) Processing:**	
(i) Scene centre lat/long:	19° 27' 0" N, 99° 1' 52" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	93.65 km × 107.53 km
(iii) Range & Azimuth pixel size:	50 m, 50 m
(iv) Number of Looks:	16
(v) DEM-orthorectified (Y/N):	Y
7. **InSAR Processing**	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	70 m
(b) Derived from Precise State Vectors:	66.6 m
(iii) Altitude of Ambiguity:	141.4 m
(iv) Range × Azimuth extents:	93.9 km × 106.2 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. **Coherence Map Parameters**	
(i) Mean:	18.9
(ii) Standard Deviation:	12.2

9. Analysis/Interpretation of Results

This differential interferogram was generated using a coarse 1 km resolution DEM, and exhibits a considerable number of phase artefacts associated with DEM errors, as a consequence of the very high vertical relief in the mountains and volcanoes surrounding the city. The image has been 'detrended' by around 15 cycles across the swath in range to correct for differences in ionospheric refraction between the two acquisitions

Despite the poor DEM quality, widespread subsidence over the entire metropolitan area of Mexico City is clearly illustrated; up to 16 phase cycles (approx. 0.5 metres of subsidence) can be clearly identified. The city is built on sedimentary deposit, and the Western boundary of the subsidence corresponds to the start of more rocky terrain. The city is essentially flat, and the quality of the DEM has had no effect on the displacement fringes observed.

The other predominant features on the interferogram are the striking fringes on the slopes of the mountain at the southeast side of the image. The spatial extent and regularity of the fringes and their contouring with the topography suggests that this feature is an artefact of the data processing. If interpreted as a DEM related effect, they represent around 1400 metres of vertical discrepancy between the terrain and the DEM. A possible alternative explanation is that the altitude of the mountain is such that underlying assumptions in the interferometric orthorectification procedures are out of their design range.

A number of other regions of less clear phase variation are evident. In general these appear to be correlated with topographic variation, and are ascribed to DEM limitations.

10. Conclusions/Recommendations

Category	Label	Grid ref.	Comments
1 class A feature	A1	99° 5' E 19° 25' N	Generalised subsidence in Mexico City (0.4 metres/year)
4 class D features	D1	98° 38' E 19° 10' N	Processing artefact
	D2	99° 5' E 19° 7' N	Topographic (DEM errors)
	D3	98° 43' E 19° 25' N	Topographic (DEM errors)
	D4	98° 45' E 19° 40' N	Topographic (DEM errors)

Categories: A *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/Feature of interest*

Latrobe Valley, Australia — OVERALL RATING: 53%

1. Marketability — Rating: Medium

Subsidence damage will soon be incorporated into Australian household insurance.

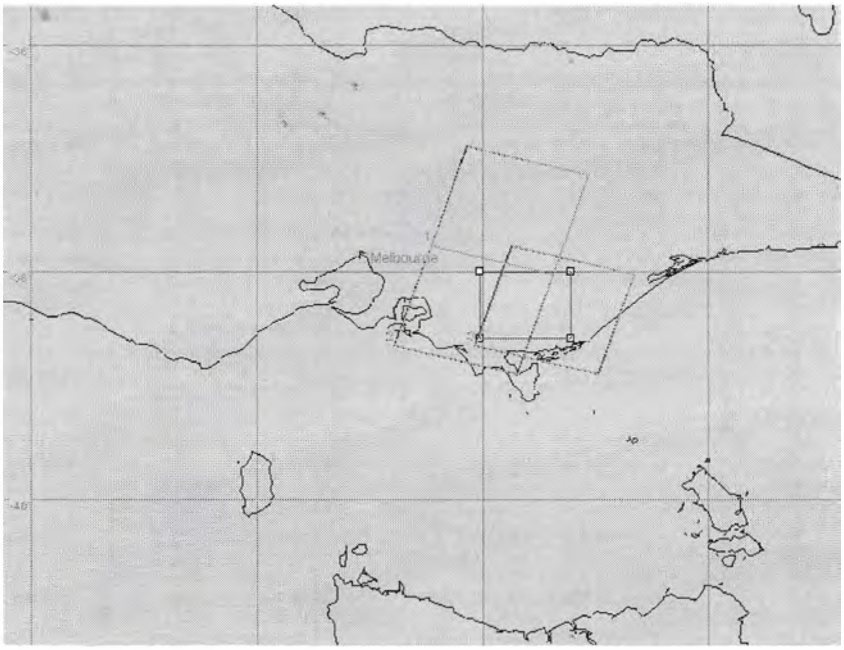
2. Subsidence category

Groundwater withdrawal.

3. Geographical extents and optimal ERS coverage

The extents of the Latrobe Valley area are approximately:

Longitude:	145° 59' E - 146° 47' E	(80 km)
Latitude:	38° 0' S - 38° 35' S	(70 km)



4. Socio-economic effects of subsidence

Unknown.

5. Customer / contact

Don Helm, Nevada Bureau of Mines and Geology, University of Nevada-Reno,
E-mail: helm@eng.morgan.edu

Ray Evans, Australian Geological Survey Organisation,
E-mail: revans@selenite.agso.gov.au

6. Subsidence rate/amount — Rating: Low

A subsidence rate of 2 cm/year has been experienced for the period 1968-1985, but there is evidence of recovery during the 1990's.

7. Ground-truth available — Rating: Poor

Ground surveys taken at infrequent intervals until 1985.

8. Land cover — Rating: Poor

Small urban area surrounded by agricultural land.

9. ERS Data availability and status — Rating: High

No suitable ascending pairs are available.
Descending: No one ideal frame is available:

1. 90% of area covered: 6 pairs with perpendicular baselines less than 50m and a temporal separation greater than 1 year.

2. 95% of area covered: 12 pairs with perpendicular baselines less than 50m and a temporal separation greater than 1 year.

Receiving Station: Alice Springs

10. DEM availability

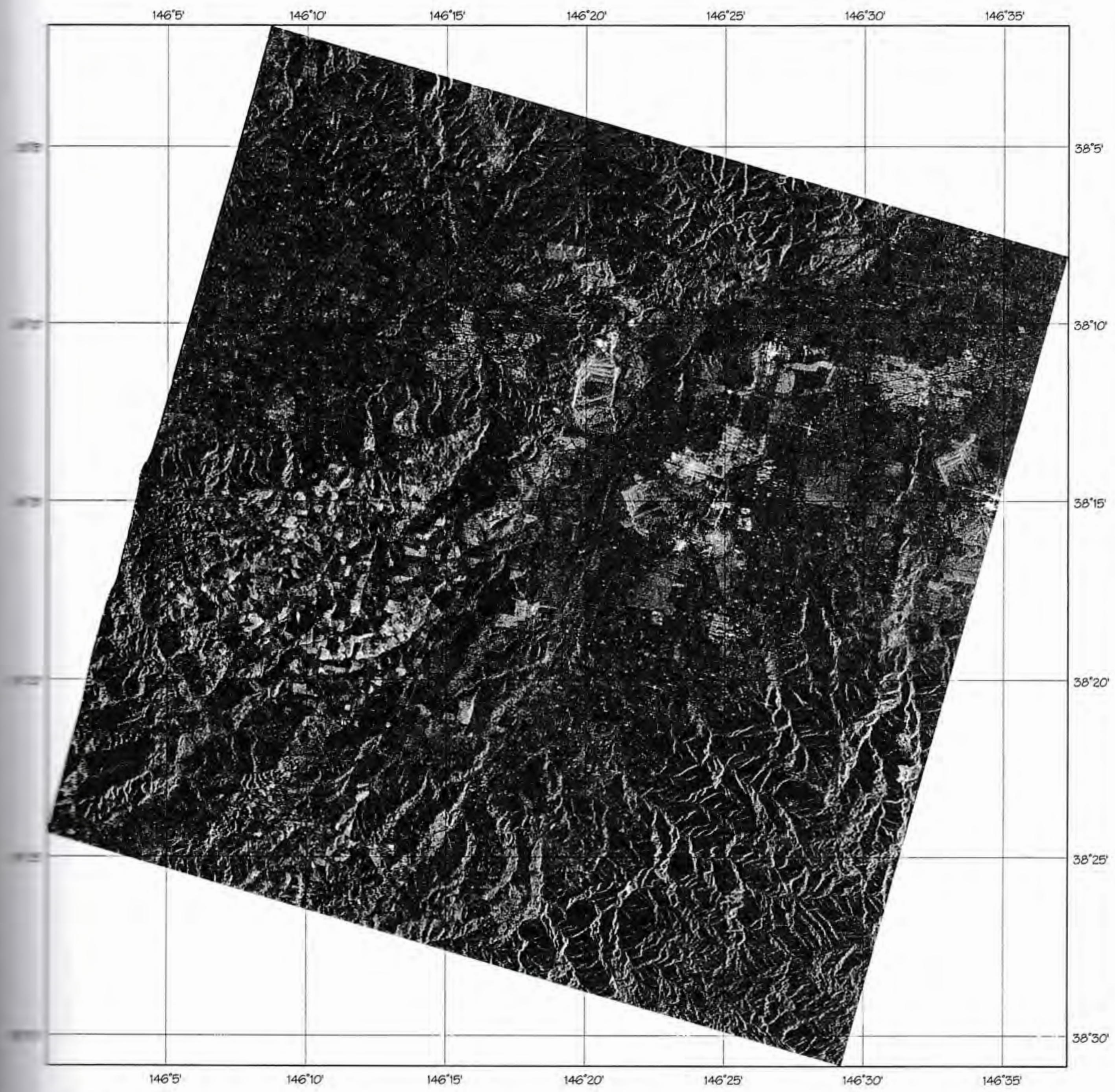
- GTOPO-30 coarse 1km resolution DEM of variable quality held in-house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in-house yet.
- Tandem INSAR.

11. Processing Status

Differential interferogram produced.

Radar amplitude for the Morwell, Latrobe Valley, Australia area

ERS scene date: 14 August 1992



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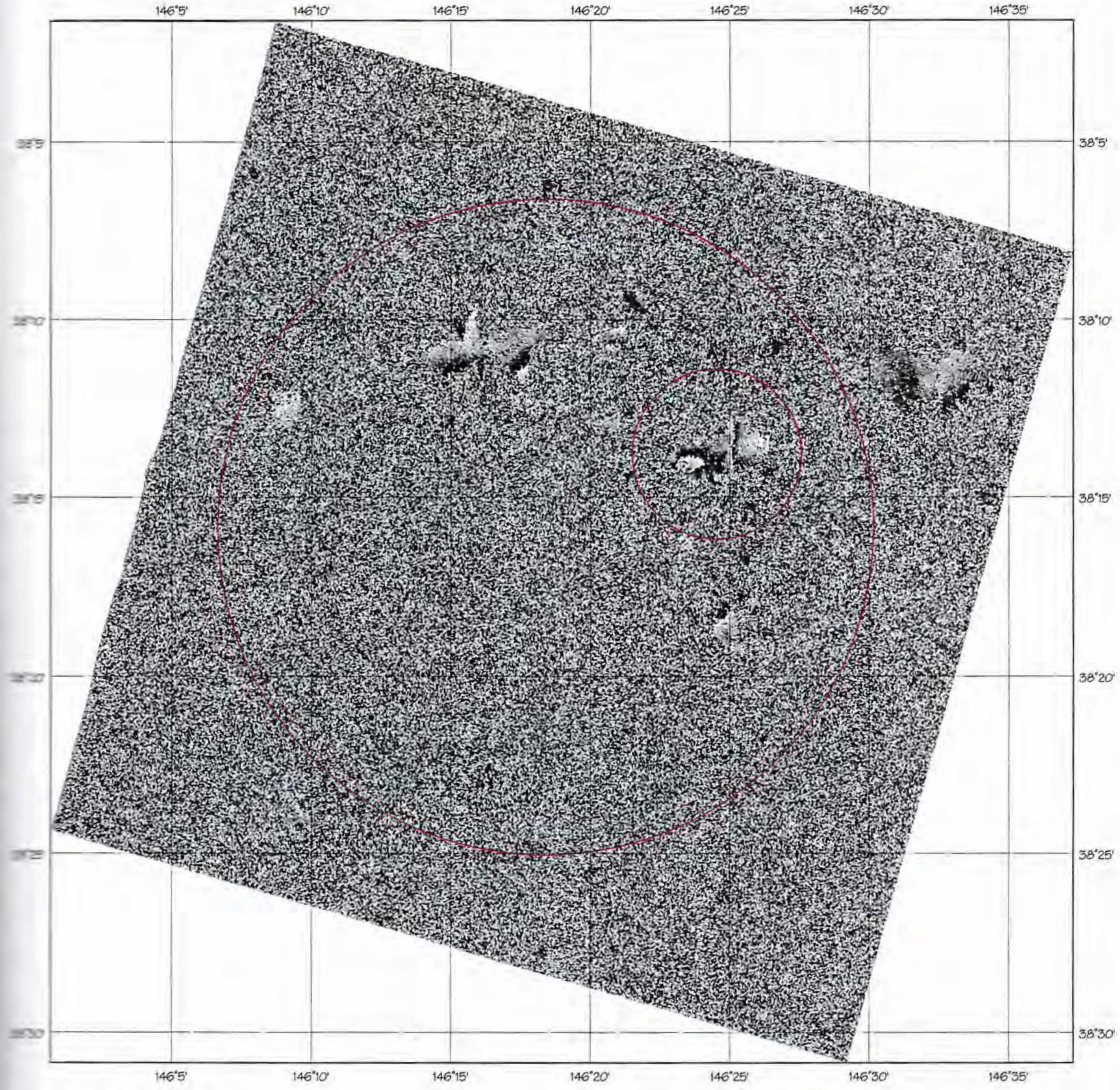
Differential interferogram for the Morwell, Latrobe Valley, Australia area

ERS scene dates: 14 August 1992 & 27 August 1995
Temporal separation: 3 years
Perpendicular baseline: 119.4 m
Altitude of ambiguity: 78.9 m

Rings indicate fringe features in this image



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SAR & InSAR Processing Summary Report	**Latrobe Valley, Australia: LAT_1 & LAT_2**

1. Image Acquisition Dates:	13/8/92 , 26/8/95
2. Temporal Separation:	3 years
3. Processing Stage (1[int], 2[diff] or 3[full]):	2
4. DEM details, if used:	
(i) Type:	GTOPO-30
(ii) Pixel size:	1 km
(iii) Accuracy – Planimetric & Vertical:	variable
5. SLC Processing:	
(i) Scene centre lat/long:	38° 21' 51" S, 146° 36' 54"E
(ii) Full- (or sub-) scene Range × Azimuth extents:	99.3 km × 108.5 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	38° 21' 23" S,146° 35° 26" E
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.1 km × 108.8 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	119 m
(b) Derived from Precise State Vectors:	119.4 m
(iii) Altitude of Ambiguity:	78.9 m
(iv) Range × Azimuth extents:	100.4 km × 108.8 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	13.75
(ii) Standard Deviation:	8.81

9. Analysis/Interpretation of Results

With the exception of the small urban areas coherence levels are very low over this scene. There is however good evidence for substantial and spatially extended subsidence in the region. There is a localised (2-km) 'hot spot' (A1) exhibiting around 3 cm of subsidence. However, to the East of this location a further phase fringe can be seen, running North/South, and this looks as if it might be part of a pattern of subsidence on a much larger scale, of order 20-30 km diameter.

10. Conclusions/Recommendations

Category	Label	Co-ordinates	Comments
1 class A feature	A1	146° 23' E 38°13' S	Localised subsidence >1 cm/year
1 class B feature	B1	146° 17' E 38° 15' S	Probable large-scale region of subsidence.

Categories: A *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/Feature of interest*

It would be informative to obtain a second pair of acquisitions over this region with a much shorter temporal separation.

Bologna, Italy — OVERALL RATING: 73%

1. Marketability — *Rating: Medium*

Subsidence in Bologna is the worst in Italy in terms of areal extent and rates experienced.
Strong interest has been expressed by two contacts at the University of Bologna, and it is anticipated that interest will also follow from the local government.

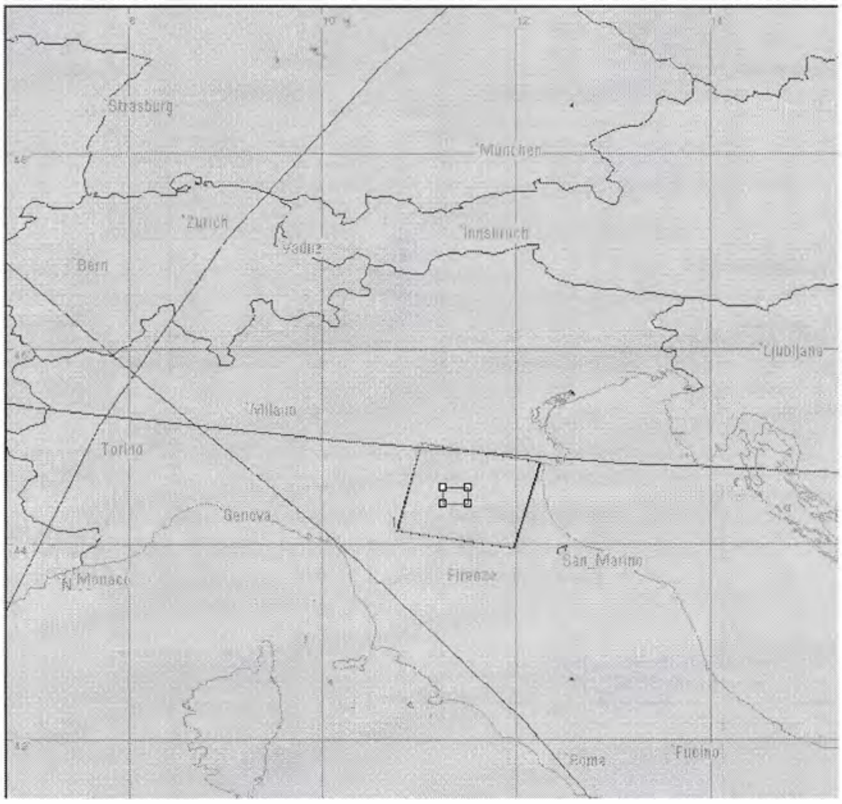
2. Subsidence category

Groundwater abstraction.

3. Geographical extents and optimal ERS coverage

The extents of the Bologna area are approximately:

Longitude:	11° 15' E - 11° 30' E	(25 km)
Latitude:	44° 25' N - 44° 35' N	(15 km)



4. Socio-economic effects of subsidence

There has been damage to buildings and monuments in the NW section of the city centre. The effects of subsidence have also damaged the sewage system.

5. Customer / contact

Prof. Ing. Gabriele Bitelli, University of Bologna, Viale, E-mail: gabriele.bitelli@mail.ing.unibo.it

Prof. Carlo Elmi, University of Bologna, E-mail: elmi@geomin.unibo.it

6. Subsidence rate/amount — *Rating: Medium*

Maximum detected rates of subsidence in the range 6-8 cm/year in the period 1983-1992. Average rates are lower.

7. Ground-truth available — *Rating: Medium*

High precision levelling surveys (about 700 benchmarks, in an area of about 460 km²) were performed in 1983, 1987 and 1992.

8. Land cover — *Rating: Medium*

The subsiding areas are urban, the surrounding areas consist of agricultural land and the Apennine mountain range.

9. ERS Data availability and status — *Rating: High*

No suitable ascending pairs available.
Descending: 64 pairs with perpendicular baselines less than 50 m and a temporal separation greater than a year.

Receiving Station: Fucino

10. DEM availability

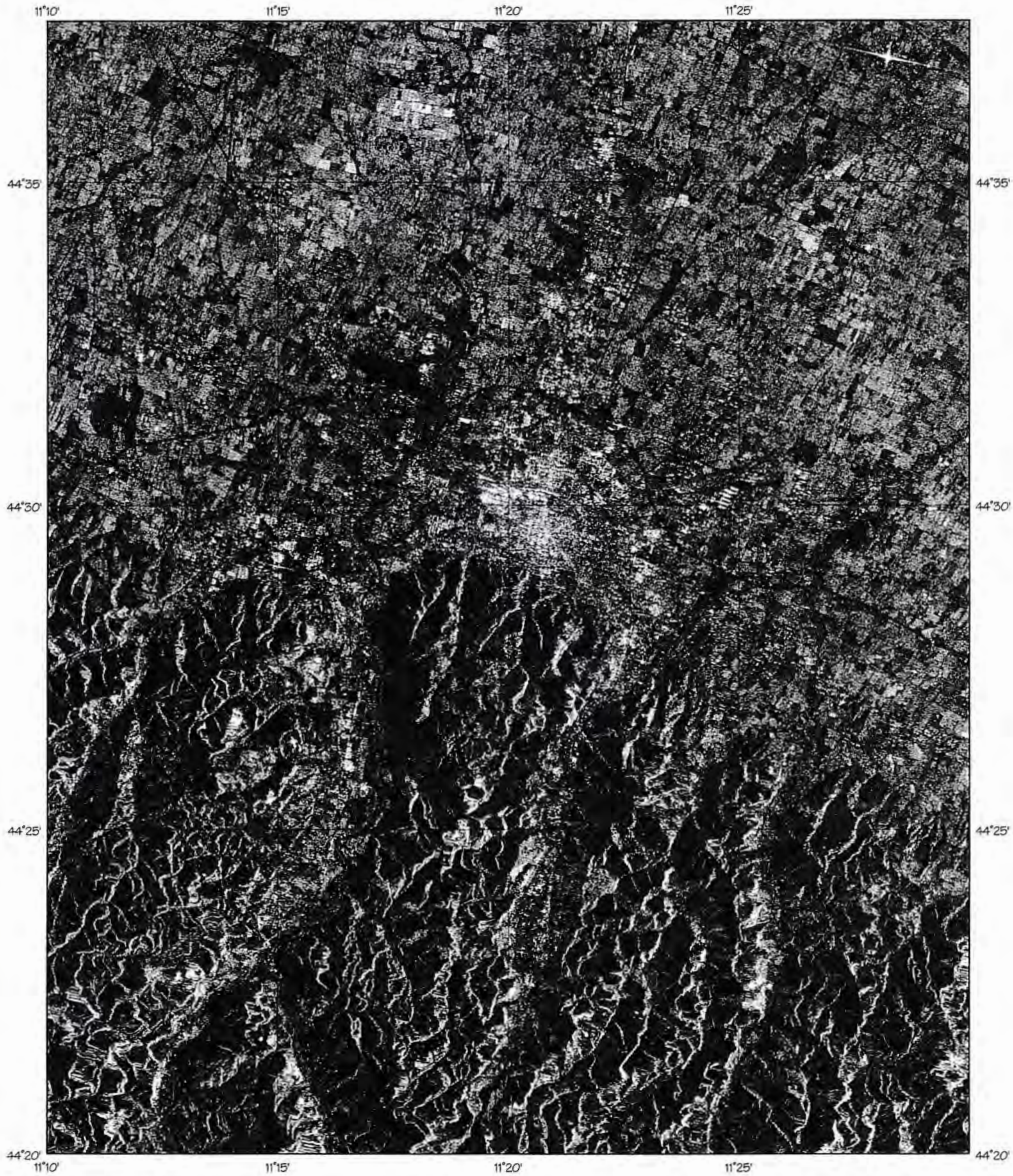
- EuroDEM 100 m × 100m grid with 30m accuracy held in-house.
- GTOPO-30 coarse 1km resolution DEM of variable quality held in-house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in-house yet.
- Tandem InSAR.

11. Processing status

Two differential interferograms produced.

Radar amplitude image for the Bologna area, Italy

ERS scene date: 1 October 1993



0 5 10 15 20 km

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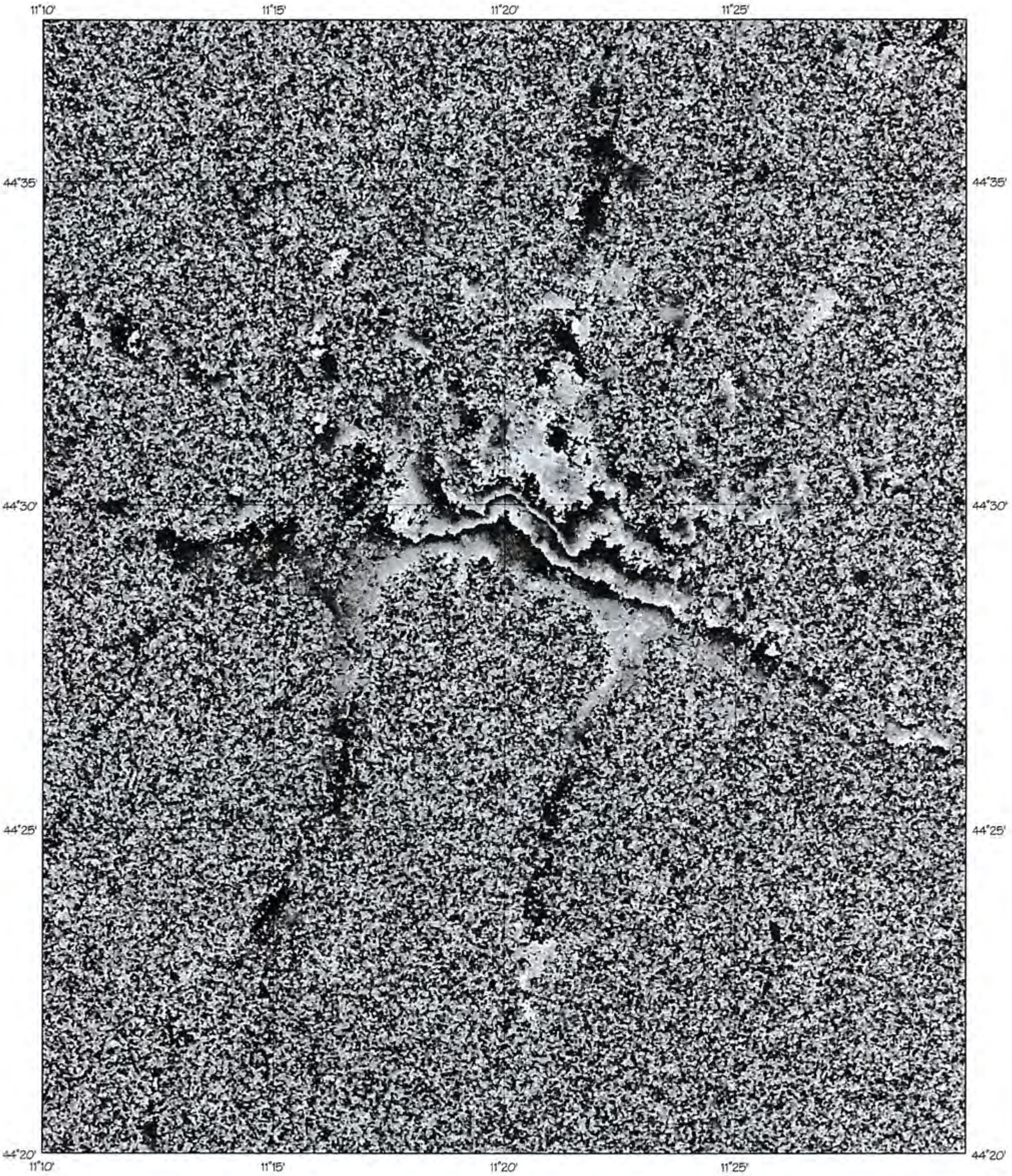
Differential interferogram for the Bologna area, Italy

ERS scene dates: 1 October 1993 & 7 January 1996
Temporal separation: 2 years 3 months
Perpendicular baseline: 80.9 m
Altitude of ambiguity: 116.4 m



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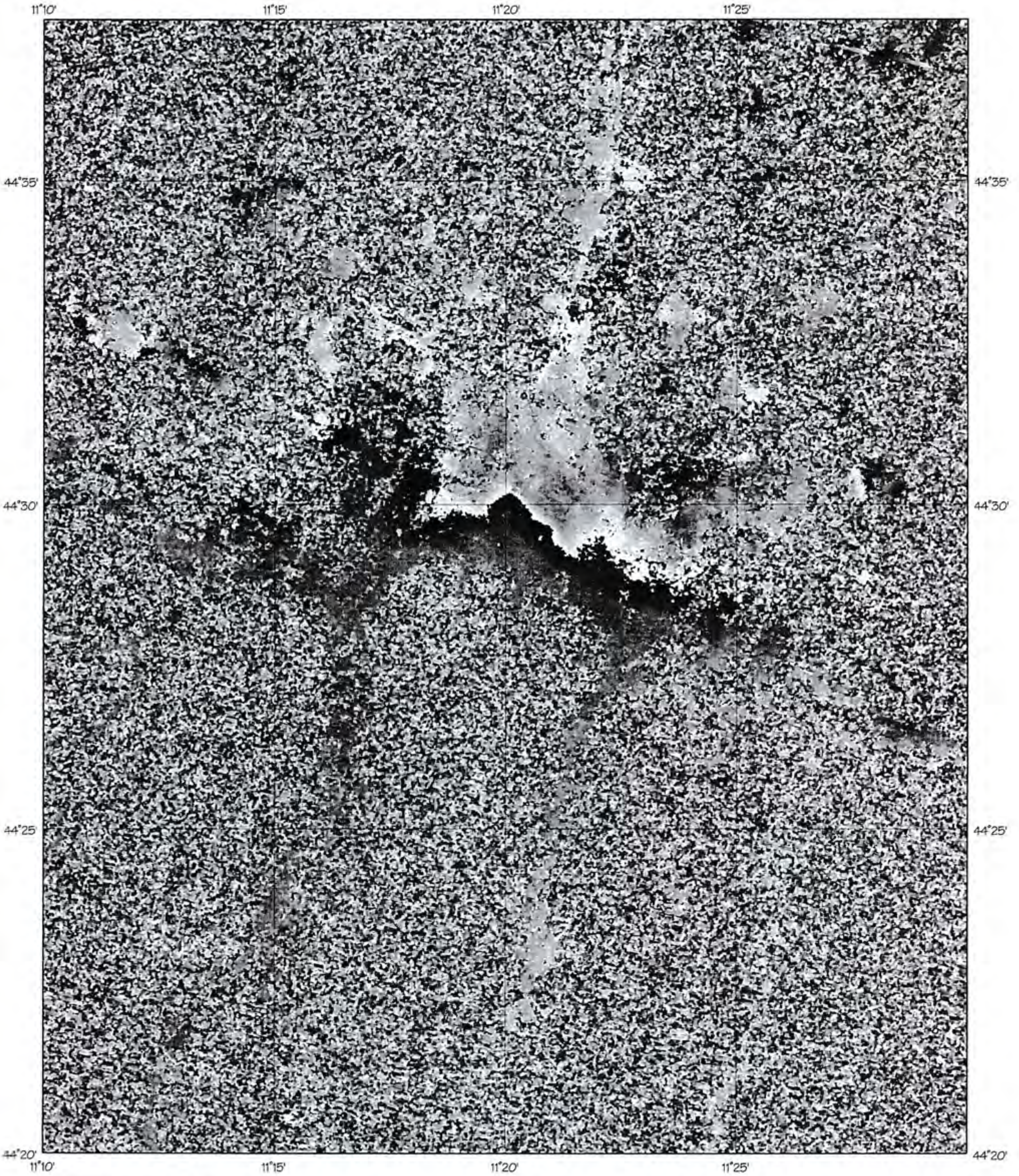
Differential interferogram for the Bologna area, Italy

ERS scene dates: 7 January 1996 & 27 January 1997
Temporal separation: 1 year
Perpendicular baseline: 14.1 m
Altitude of ambiguity: 667.8 m



0 5 10 15 20 km

SAR & InSAR Processing Summary Report — **Bologna, Italy: BOL_1 & BOL_2**

1. **Image Acquisition Dates:**	1/10/93, 7/1/96
2. **Temporal Separation:**	2 years 3 months
3. **Processing Stage (1[int], 2[diff] or 3[full]):**	2
4. **DEM details, if used:**	
(i) Type:	GeoDEM
(ii) Pixel size:	(3 arc seconds ~100 m)
(iii) Accuracy – Planimetric & Vertical:	30 m (vertical)
5. **SLC Processing:**	
(i) Scene centre lat/long:	44° 28' 34" N, 11° 29' 03" E
(ii) Full- (or sub-) scene Range × Azimuth extents:	99.3 km × 106.5 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. **Ground-range PRI (Amplitude Image) Processing:**	
(i) Scene centre lat/long:	44° 28' 52" N,11° 26' 26" E
(ii) Full- (or sub-) scene Range × Azimuth extents:	98.7 km × 106.6 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. **InSAR Processing**	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	75 m
(b) Derived from Precise State Vectors:	80.9 m
(iii) Altitude of Ambiguity:	116.4 m
(iv) Range × Azimuth extents:	98.9 km × 104.4 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. **Coherence Map Parameters**	
(i) Mean:	14.09
(ii) Standard Deviation:	10.03

9. Analysis/Interpretation of Results

The Bologna region is predominantly agricultural and/or vegetated. The coherence is effectively zero over the majority of the scene, with the exception of the urban regions and the city of Bologna.

The predominant feature of both differential interferograms is significant phase variation over the city of Bologna, most clearly evident on the 2-year separation interferogram. A sufficient number of towns are visible on the interferogram to be confident that the phase variation observed over Bologna is not a feature of some large scale phase trend, but is a feature of the data. The rate of movement is not however consistent between the two acquisitions, with a total of 4 phase cycles evident on the 27 month separation, and only 1 phase cycle on the subsequent 12 month separation, suggesting that the phenomenon causing the effect is reducing in magnitude with time. The interferometric fringes are roughly parallel to the edge of the mountain range to the South of the city.

The pattern of the interferometric phase variation is atypical for urban subsidence, without any clear central focus; but is consistent with ground truth measurements that show a focus for the subsidence in the agricultural regions north of the city of Bologna.

10. Conclusions/Recommendations

Category	Label	Co-ordinates	Comments
1 class A feature	A1	11° 20' E 44° 30' N	Extended subsidence over the city of Bologna

Categories: A *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/Feature of interest*

SAR & InSAR Processing Summary Report — Bologna, Italy: BOL_2 & BOL_3

1. Image Acquisition Dates:	7/1/96, 27/1/97
2. Temporal Separation:	1 year
3. Processing Stage (1[int], 2[diff] or 3[full]):	2
4. DEM details, if used:	
(i) Type:	GeoDEM
(ii) Pixel size:	(3 arc seconds ~100 m)
(iii) Accuracy – Planimetric & Vertical:	30 m (vertical)
5. SLC Processing:	
(i) Scene centre lat/long:	44° 29' 49" N, 11° 29' 28" E
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	44° 29' 56" N,11° 26' 48" E
(ii) Full- (or sub-) scene Range × Azimuth extents:	98.7 km × 106.9 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	14 m
(b) Derived from Precise State Vectors:	14.1 m
(iii) Altitude of Ambiguity:	667.8 m
(iv) Range × Azimuth extents:	99.1 km × 105.1 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	14.22
(ii) Standard Deviation:	10.62

9. Analysis/Interpretation of Results

The Bologna region is predominantly agricultural and/or vegetated. The coherence is effectively zero over the majority of the scene, with the exception of the urban regions and the city of Bologna.

The predominant feature of both differential interferograms is significant phase variation over the city of Bologna, most clearly evident on the 2-year separation interferogram. A sufficient number of towns are visible on the interferogram to be confident that the phase variation observed over Bologna is not a feature of some large scale phase trend, but is a feature of the data. The rate of movement is not however consistent between the two acquisitions, with a total of 4 phase cycles evident on the 27 month separation, and only 1 phase cycle on the subsequent 12 month separation, suggesting that the phenomenon causing the effect is reducing in magnitude with time. The interferometric fringes are roughly parallel to the edge of the mountain range to the South of the city.

The pattern of the interferometric phase variation is atypical for urban subsidence, without any clear central focus; but is consistent with ground truth measurements that show a focus for the subsidence in the agricultural regions north of the city of Bologna.

10. Conclusions/Recommendations

Category	Label	Co-ordinates	Comments
1 class A feature	A1	11° 20' E 44° 30' N	Extended subsidence over the city of Bologna

Categories: A *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/Feature of interest*

Ravenna, Italy — OVERALL RATING: 67%

1. Marketability — *Rating: Medium*

Over the last 30 years Ravenna has been progressively sinking; the town is particularly vulnerable to subsidence due to its proximity to the sea. The Municipal Geological Office has closely monitored the subsidence after the intervention of the state laying down laws for the environmental protection of the town.

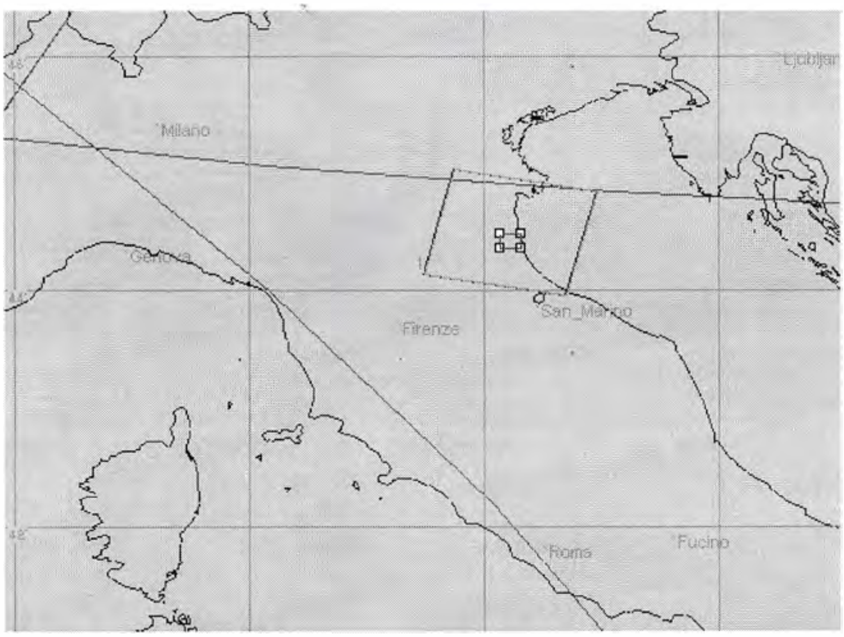
2. Subsidence category

Groundwater withdrawal, with a significant contribution from natural gas production.

3. Geographical extents and optimal ERS coverage

The extents of the Ravenna area are approximately:

Longitude:	12° 08' E - 12° 09' E	(10 km)
Latitude:	44° 22' N - 44° 29' N	(8 km)



4. Socio-economic effects of subsidence

Subsidence has caused serious damage to the industrial area and harbour infrastructures which made it necessary to build protection walls and raise the quays. Damage to monuments has also occurred.

5. Customer / contact

Marco Anzidei, Istituto Nazionale Di Geofisica, Rome, Italy, E-mail: ANZIDEI@ing750.ingrm.it

Dr. Ing. Pietro Teatini, Department of Mathematical Models for Applied Sciences, University of Padova, Italy, E-mail: teatini@dmsa.unipd.it

Prof. Giuseppe Gambolati, Department of Mathematical Models for Applied Sciences, University of Padova, Italy, E-mail: gambo@dmsa.unipd.it

6. Subsidence rate/amount *Rating: Low*

The current subsidence rate is estimated to be about 1 cm/year.

7. Ground-truth available *Rating: Medium*

Levelling data available from Instituto Geografico Militare Italiano and the University of Padova.

8. Land cover *Rating: Medium*

Subsiding areas are urban.

9. ERS Data availability and status *Rating: High*

No suitable ascending pairs available.
Descending, 21 pairs with perpendicular baselines less than 50 m and a temporal separation greater than a year.

Receiving Station: West Freugh

10. DEM availability

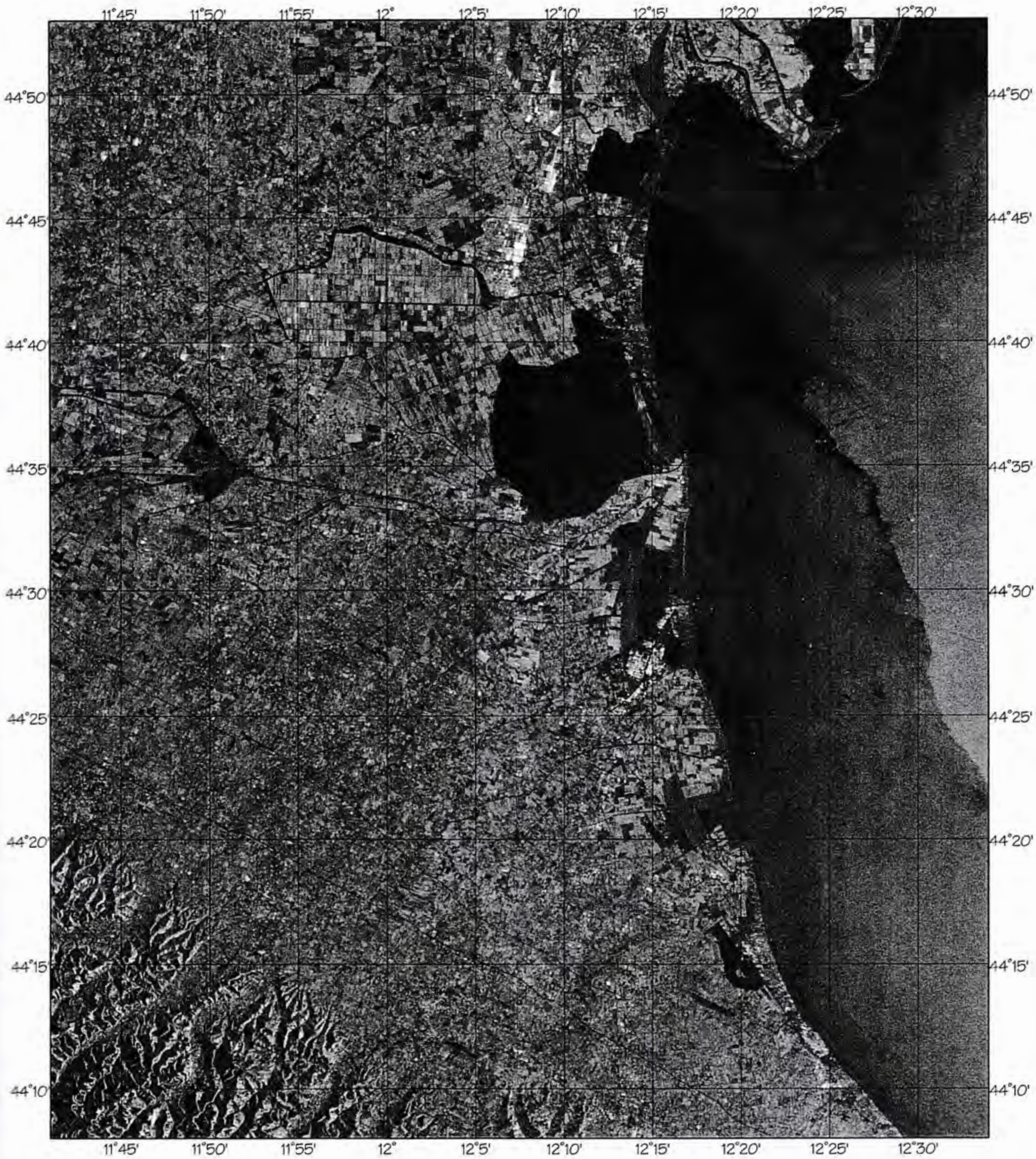
- EuroDEM 100 m × 100m grid with 30m accuracy held in-house.
- GTOPO-30 coarse 1km resolution DEM of variable quality held in-house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in-house yet.
- Tandem InSAR.

11. Processing status

Differential interferogram produced.

Radar amplitude image for the Ravenna area

ERS-1 scene date: 1 November 1992



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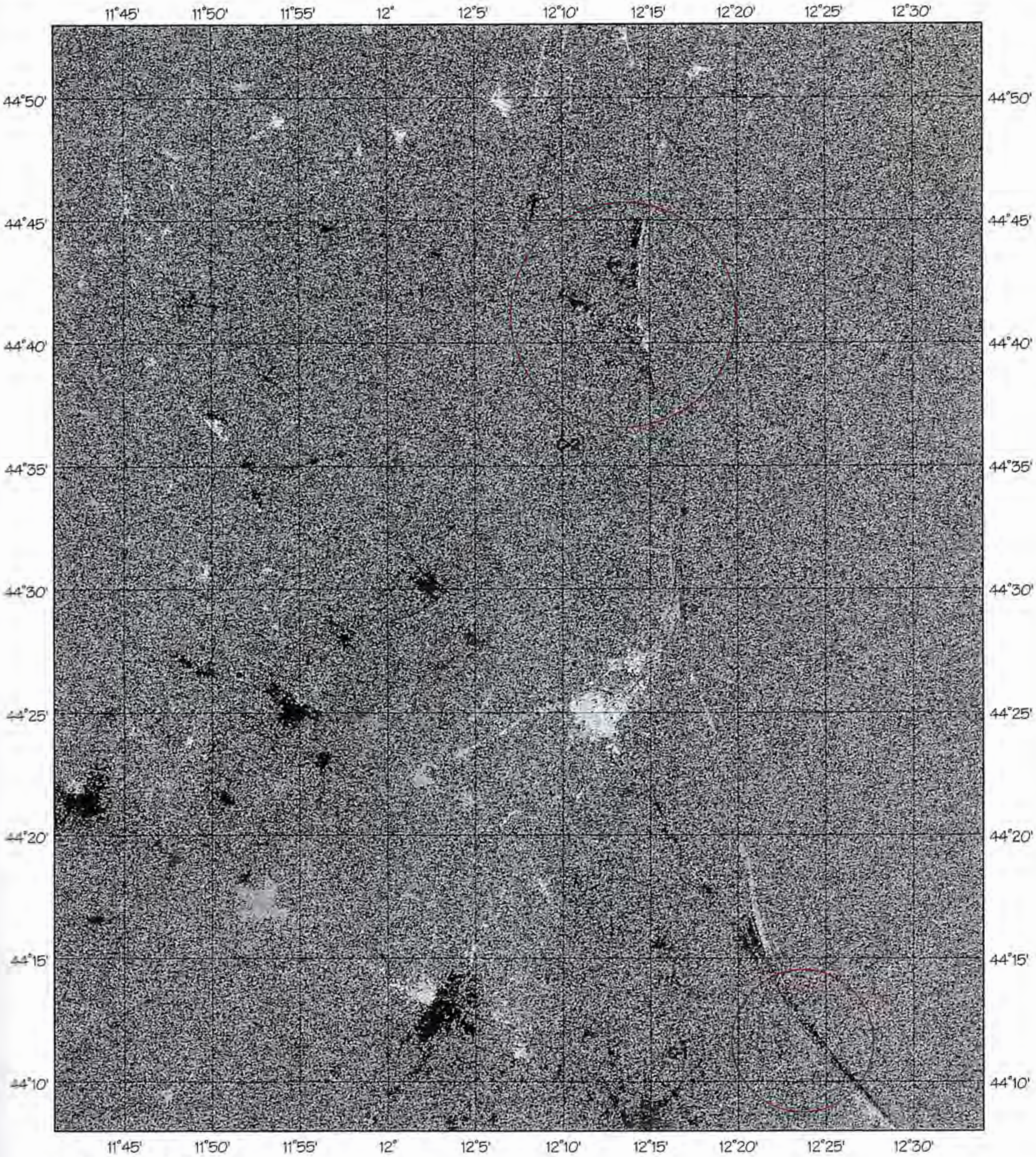
Differential interferogram for the Ravenna area

ERS-1 scene dates: 1 November 1992 & 21 November 1993
Temporal separation: 1 year
Perpendicular baseline: 65.4 m
Altitude of ambiguity: 144.0 m

Rings indicate fringe features in this image



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SAR & InSAR Processing Summary Report **Ravenna: RAV_1 & RAV_2**

1. Image Acquisition Dates:	1/11/92, 21/11/93
2. Temporal Separation:	1 year
3. Processing Stage (1[int], 2[diff] or 3[full]):	2
4. DEM details, if used:	
(i) Type:	GeoDEM
(ii) Pixel size:	(3 arc seconds ~100m)
(iii) Accuracy – Planimetric & Vertical:	30 m (vertical)
5. SLC Processing:	
(i) Scene centre lat/long:	44° 27' 25" N, 12° 11' 06" E
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	44° 27' 25" N, 12° 09' 06" E
(ii) Full- (or sub-) scene Range × Azimuth extents:	104.1 km × 109.8 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	66 m
(b) Derived from Precise State Vectors:	65.4 m
(iii) Altitude of Ambiguity:	143.9 m
(iv) Range × Azimuth extents:	104.1 km × 109.8 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	21.13
(ii) Standard Deviation:	12.87

9. Analysis/Interpretation of Results

Land use in the Ravenna region is primarily agricultural, as is illustrated by the radar amplitude image. As a consequence the interferometric coherence is limited to the towns and villages of the region, and very little information can be inferred from the differential interferogram.

The variations in grey-scale of the isolated regions of high coherence in the interferogram are not in general of any significance; the abrupt changes from black to white correspond to a 2π phase boundary, and in general the magnitude of local phase differences are a small fraction of a phase cycle.

There is a possible indication of up to 1.5 cm of movement in the coastal developments to the southeast (12° 25' E, 44° 11' N) and the north (12° 14' E, 44° 40' N) of the figure.

The amplitude image and the interferogram have been corrected for topography using a digital elevation model, and the georeference provided by the grid overlay is accurate to of order 100 m.

10. Conclusions/Recommendations

Category	Label	Grid ref.	Comments
2 class C features	C1	12° 25' E 44° 11' N	Possible subsidence (1/2 cycle, 1.5 cm)
	C2	12° 14' E 44° 40' N	Possible subsidence (1/2 cycle, 1.5 cm)

Categories: **A** *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/Feature of interest*

Since coherence is too poor over a temporal separation of 1 year, and the rates of subsidence known to be occurring are small (1 cm/year), no further data will be analysed.

Tokyo, Kanto Basin, Japan — OVERALL RATING: 73%

1. Marketability — *Rating: Good*

Subsidence has been a problem in Tokyo ever since the rapid industrial and economic growth experienced following the Second World War. A number of good contacts have been established in Japan. One of these, Dr Sato, recently presented our interferometric results at a research conference in Tokyo. Feedback from this conference has been positive and we anticipate that further work will be commissioned.

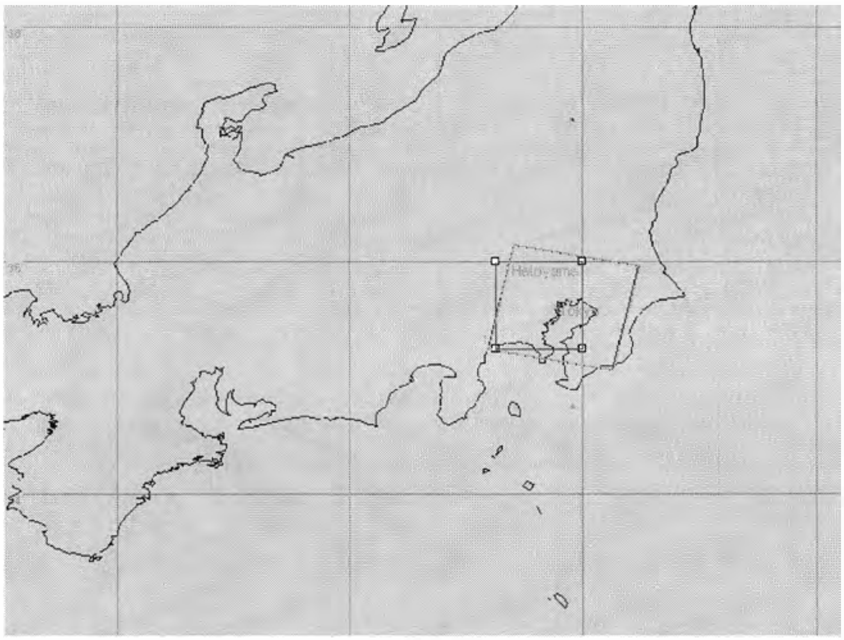
2. Subsidence category

Groundwater abstraction.

3. Geographical extents and optimal ERS coverage

The extents of the Kanto basin area are approximately:

Longitude:	139° 15' E -140° 0' E	(70 km)
Latitude:	35° 15' N - 36° 0' N	(80 km)



4. Socio-economic effects of subsidence

Eastern Tokyo has subsided over 4m since 1920 and as a consequence two million people now live below high tide level, necessitating massive flood defence systems.

5. Customer / contact

Murakami Masaki, Geodetic R&D Office, Geographical Survey Institute, Japan,
E-mail: masaki-m@gsi-mc.go.jp

Dr Isao Sato, Geologic Remote Sensing Section, Environmental Geology Department, Geological Survey of Japan, E-mail: isao@gsj.go.jp

Takashi Nishidai, JGI, Tokyo, E-mail: nishidai@jgi.co.jp

6. Subsidence rate/amount *Rating: High*

A total area of 93 km² subsided by 3 cm or more in the period 1993-1994, corresponding to a season of unusual water shortage around August 1994.

7. Ground-truth available *Rating: Poor*

Currently unknown.

8. Land cover *Rating: Good*

Very large urban area.

9. ERS Data availability and status *Rating: Low*

No suitable ascending pairs available.
Descending:
90% of specified area covered: 4 pairs with a perpendicular baselines less than 50m and a temporal separation greater than a year

Receiving Station: Kumamoto

10. DEM availability

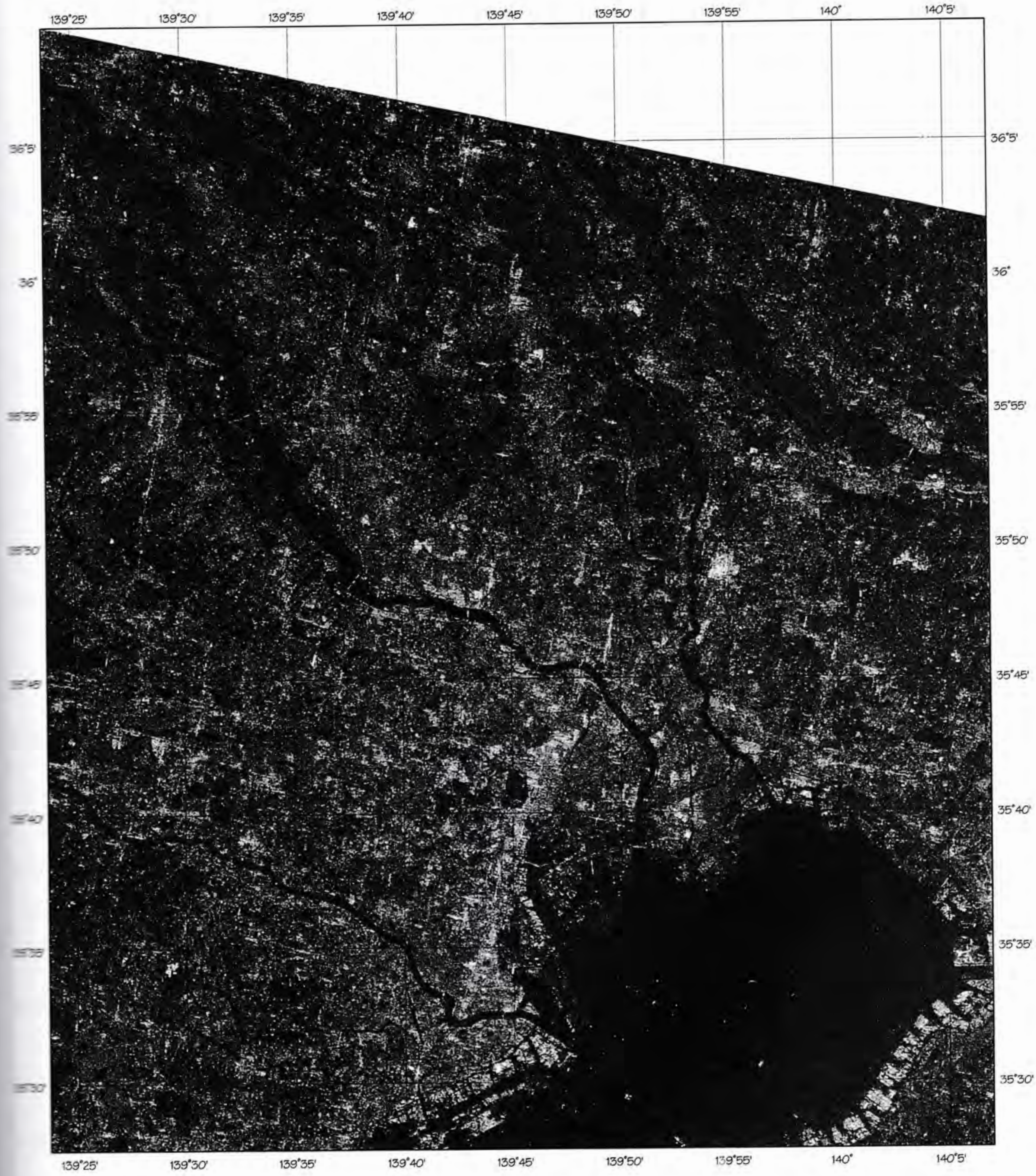
- GTOPO-30 coarse 1km resolution DEM of variable quality held in-house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in-house yet.
- Tandem InSAR.

11. Processing status

Differential interferogram produced.

Radar amplitude image for the Tokyo metropolis and Saitama prefecture

ERS scene date: 16 April 1993



0 5 10 15 20 25 km

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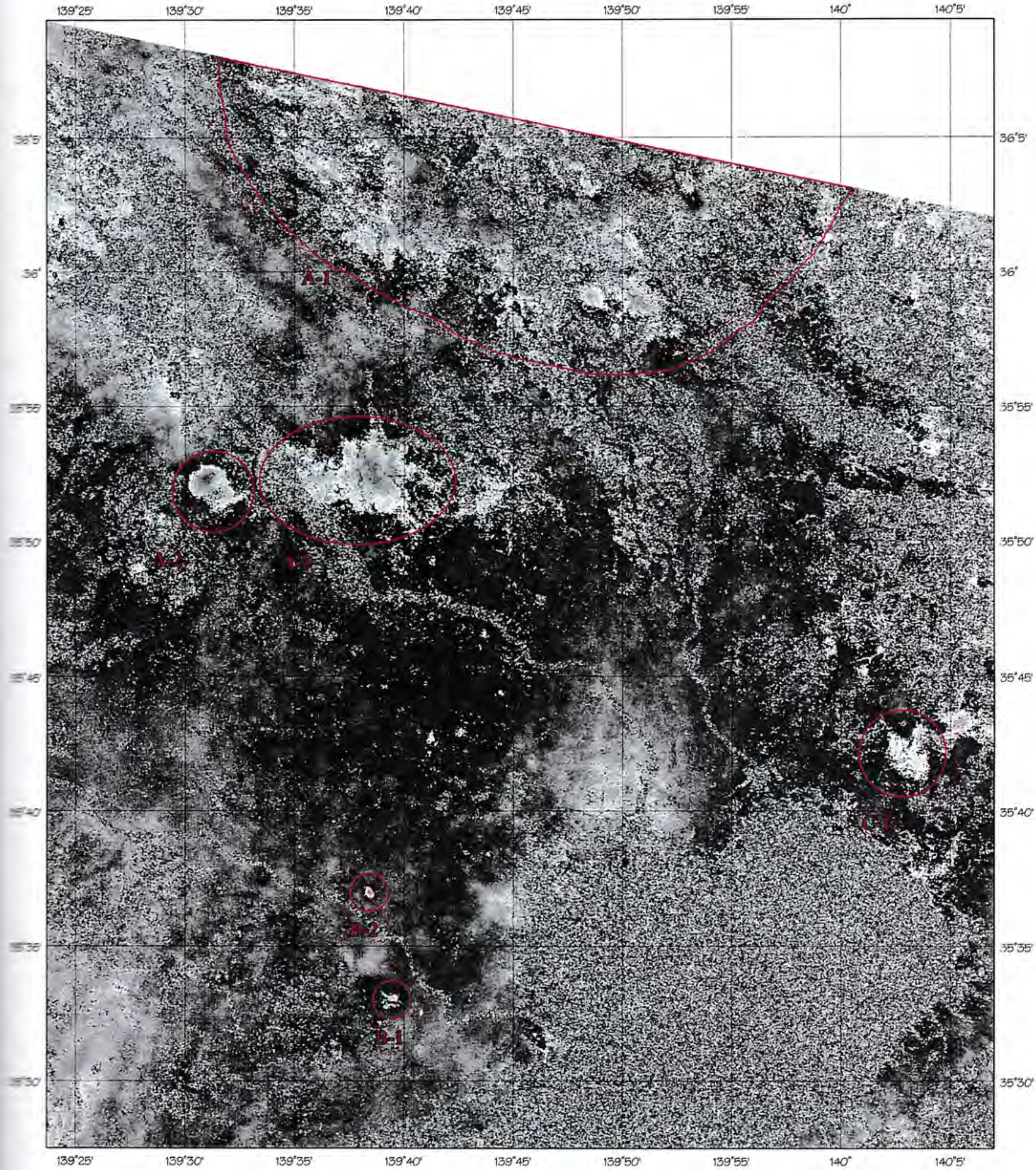
Differential interferogram for the Tokyo metropolis and Saitama prefecture

ERS scene dates: 16 April 1993 & 5 November 1995
Temporal separation: 2 years 7 months
Perpendicular baseline: 16.5 m
Altitude of ambiguity: 570.7 m

Rings indicate fringe features in this image



0 5 10 15 20 25 km

SAR & InSAR Processing Summary Report	**Tokyo, Kanto Basin, Japan: KAN_1 & KAN_2**

1. **Image Acquisition Dates:**	16/4/93, 5/11/95
2. **Temporal Separation:**	2 years 7 months
3. **Processing Stage (1[int], 2[diff] or 3[full]):**	2
4. **DEM details, if used:**	
(i) Type:	Japanese DEM
(ii) Pixel size:	50m
(iii) Accuracy – Planimetric & Vertical:	unknown
5. **SLC Processing:**	
(i) Scene centre lat/long:	35° 35' 45" N, 139° 48' 18" E
(ii) Full- (or sub-) scene Range × Azimuth extents:	99.3 km × 106.5 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. **Ground-range PRI (Amplitude Image) Processing:**	
(i) Scene centre lat/long:	35° 35' 51" N 139° 48' 17" E
(ii) Full- (or sub-) scene Range × Azimuth extents:	98.6 km × 106.8 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. **InSAR Processing**	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	10 m
(b) Derived from Precise State Vectors:	16.54 m
(iii) Altitude of Ambiguity:	569.28 m
(iv) Range × Azimuth extents:	99.1 km × 106.2 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. **Coherence Map Parameters**	
(i) Mean:	21.95
(ii) Standard Deviation:	18.40

9. Analysis/Interpretation of Results

Figure 1

Radar amplitude image for 16-Apr-93

Figure 2

ERS interferogram, data acquired 16-Apr-93 and 05-Nov-95
Temporal separation: 2 years and 7 months
Baseline: 16.54 metres
Altitude of ambiguity: 569.28 metres

This differential ERS interferogram covers the Tokyo Metropolitan area and the southwest corner of the Saitama prefecture. The interferogram has been corrected for topography using a digital elevation model (DEM), and the geo-referencing defined by the superimposed grid is accurate to better than 100 m.

Historically the Kanto basin has experienced extensive subsidence associated with ground water extraction, of up to 4 metres over the last century; steps have been taken over the last few decades to stabilise groundwater levels, and the interferogram is consequently of considerable interest.

Despite the temporal separation the interferogram is generally of good quality over the urban areas, with high coherence and limited atmospheric phase noise. A number of subsidence related features are evident on the interferogram. Most notable is a large area to the north of the scene (139° 44' E, 36° 4' N) for which two clear cycles of phase are evident. This feature extends beyond the limit of the scene used therefore the full magnitude of the subsidence cannot be determined, except to say that the subsidence rate is at least 3 cm/year and that the area covered exceeds 480 km^2. Several smaller subsidence features are also evident, all with a comparable subsidence rate (of order 1 cm/year), but varying in geographic extent. There are two medium size regions of subsidence to the north west of the scene (139° 31' E, 35° 52' N, and 139° 38' E, 35° 52.5' N) of dimensions approximately 3 and 6 km respectively. Two much more localised (1km) subsidence features are also apparent towards Tokyo bay (139° 39' E, 35° 33' N and 139° 38' E, 35° 37' N). A possible subsidence feature of about 15 km^2 in area is also visible (140° 3' E, 35° 42' N).

On a larger scale the interferogram exhibits a degree of consistent phase curvature from East to West and from South to North, of magnitude of order ½ a phase cycle. This may well be due to limitations of the orbit data or large-scale atmospheric variations, and is not necessarily indicative of subsidence.

Category	Label	Grid ref.	Comments
3 class A features	A1	139° 44' E 36° 4' N	At least 480 km^2
	A2	139° 31' E 35° 52' N	9 km^2
	A3	139° 38' E 35° 52.5' N	36 km^2
2 class B features	B1	139° 39' E 35° 33' N	4 km^2
	B2	139° 38' E 35° 37' N	1 km^2
1 class C feature	C1	140° 03' E 35° 42' N	15 km^2

Categories: A *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/Feature of interest*

10. Conclusions/Recommendations

In view of the good coherence over Tokyo and relatively slow subsidence rates, it would be worthwhile to examine a further pair with a longer temporal separation, if suitable acquisitions are available.

Rotterdam, Netherlands OVERALL RATING: 73%

1. Marketability *Rating: Medium*

Rotterdam has been affected by the gas extraction activities of the Shell Group, and the site was suggested to us by a contact we have made at Shell.

2. Subsidence category

Gas extraction.

3. Geographical extents and optimal ERS coverage

The extents of the Rotterdam area are approximately:

Longitude:	4° 15' E – 4° 45' E	(50 km)
Latitude:	51° 45' N - 52° 0' N	(25 km)

4. Socio-economic effects of subsidence

Main concerns are over the extreme sensitivity of the Rotterdam harbour infrastructure to subsidence.

5. Customer / contact

Adriaan Houtenbos, Department Head, Topographical Department, NAM, Shell Group
E-mail: A.P.E.Houtenbos@OPENMAIL.XTD.namass.simis.com

6. Subsidence rate/amount *Rating: Low*

A subsidence bowl with a diameter of a few kilometres has developed.
The subsidence rate experienced since 1992 is a few mm/year.

7. Ground-truth available *Rating: Medium*

Three second order levelling surveys are available.

8. Land cover *Rating: Good*

Large urban area surrounded by agricultural land.

9. ERS data availability and status *Rating: High*

No suitable ascending pairs.
Descending: 56 pairs with perpendicular baselines less than 50m and a temporal separation greater than a year.

Receiving Station: Fucino

10. DEM availability

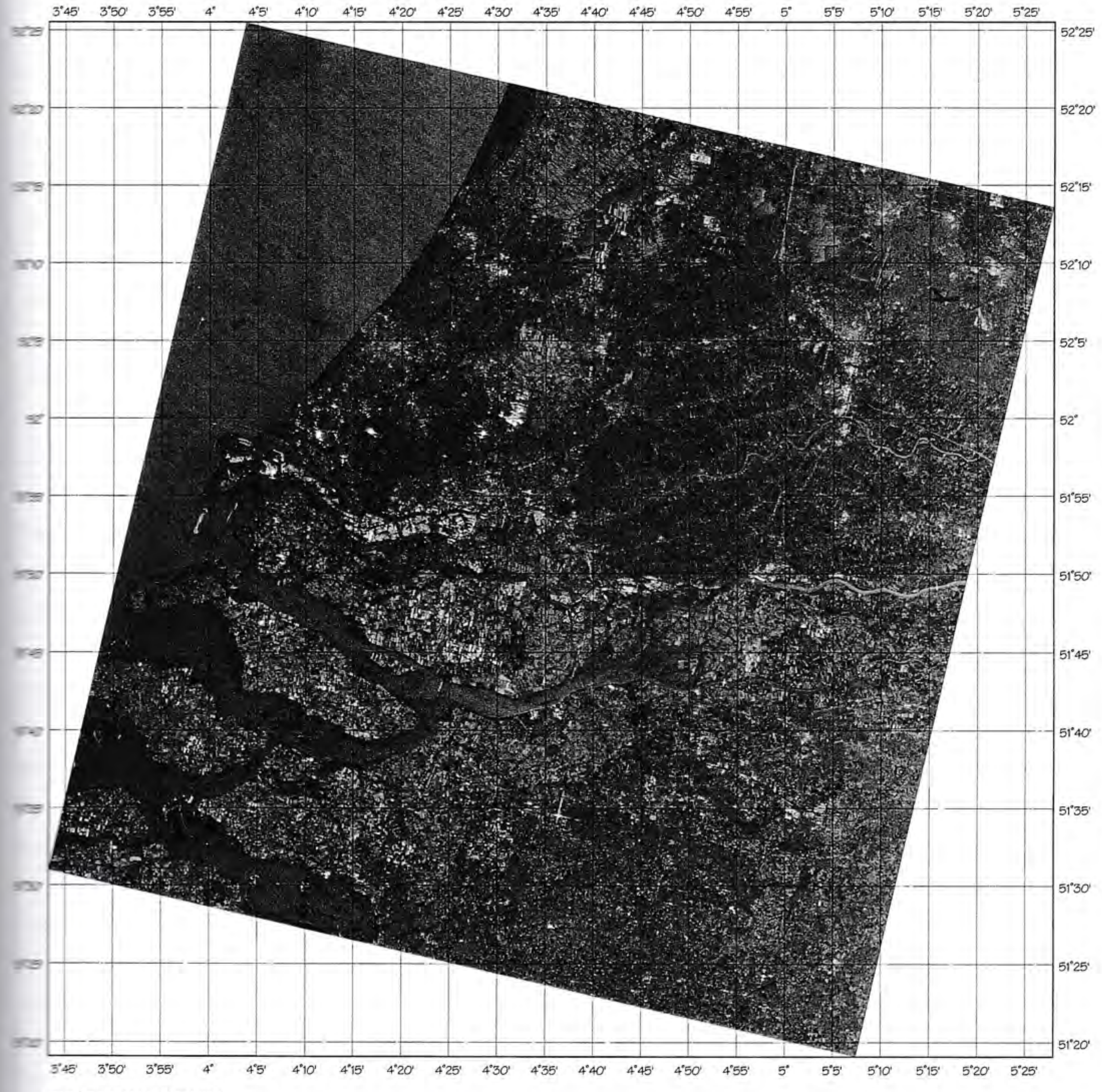
- EuroDEM 100 m × 100m grid with 30m accuracy held in-house.
- GTOPO-30 coarse 1km resolution DEM of variable quality held in-house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in-house yet.
- Tandem InSAR.

11. Processing status

Interferogram produced.

Radar amplitude image for the Rotterdam area

ERS scene date: 3 October 1993



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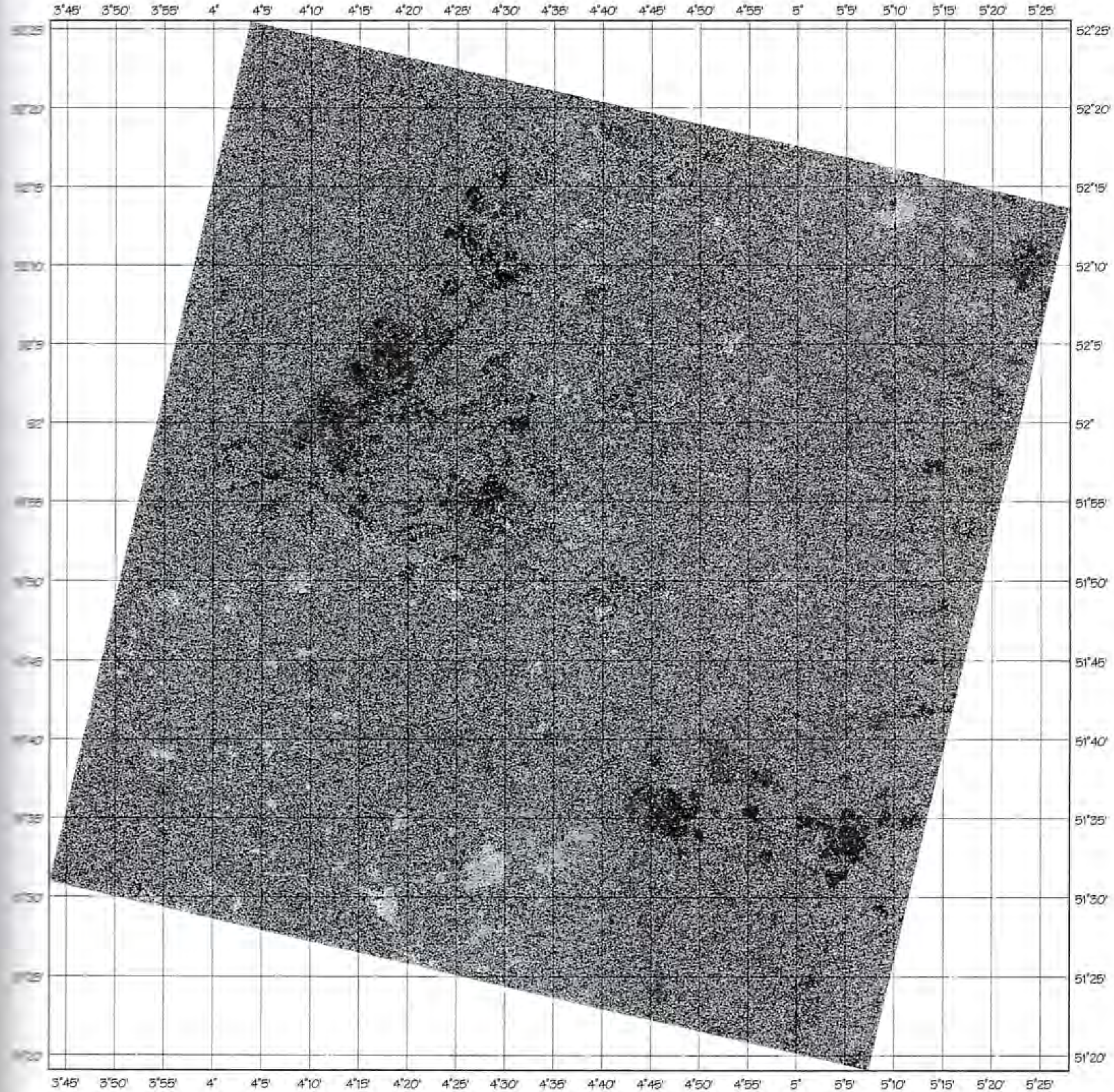
Interferogram for the Rotterdam area

ERS scene dates: 3 October 1993 & 16 October 1996
Temporal separation: 3 years
Perpendicular baseline: 133.7 m
Altitude of ambiguity: 70.4 m



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SAR & InSAR Processing **Rotterdam, Netherlands: ROT_1 & ROT_2**
Summary Report

1. **Image Acquisition Dates:**	3/10/93, 16/10/96
2. **Temporal Separation:**	3 years
3. **Processing Stage (1[int], 2[diff] or 3[full]):**	1
4. **DEM details, if used:**	none
(i) Type:	
(ii) Pixel size:	
(iii) Accuracy – Planimetric & Vertical:	
5. **SLC Processing:**	
(i) Scene centre lat/long:	51° 52' 59" N, 4° 36' 18" E
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.5 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. **Ground-range PRI (Amplitude Image) Processing:**	
(i) Scene centre lat/long:	51° 51' 40" N,4° 35' 22" E
(ii) Full- (or sub-) scene Range × Azimuth extents:	98.9 km × 106.6 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	N
7. **InSAR Processing**	
(i) Interferogram or DEM-orthorectified Differential:	Interferogram
(ii) Perpendicular Baseline:	
(a) Nominal:	134 m
(b) Derived from Precise State Vectors:	133.7 m
(iii) Altitude of Ambiguity:	70.4 m
(iv) Range × Azimuth extents:	98.9 km × 104.27 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. **Coherence Map Parameters**	
(i) Mean:	14.27
(ii) Standard Deviation:	9.9

9. Analysis/Interpretation of Results

The land use in this scene is predominantly agricultural, and as a consequence the coherence levels are effectively zero over the three year temporal separation, except over some regions of Rotterdam itself and a number of isolated towns covered by the scene.

It is difficult to draw any firm conclusions from this data set, other than that there is no obvious evidence of any significant or extended subsidence within the Rotterdam area.

10. Conclusions/Recommendations

It is possible that an improved result would be obtained from processing of a further pair with a reduced temporal separation. However in our view this is unlikely; the characteristics of the region appear to make it unsuited to interferometric subsidence mapping.

Bangkok, Thailand — OVERALL RATING: 67%

1. Marketability — *Rating: Medium*

Extensive surveying is conducted twice yearly by the Asian Institute of Technology, with a subsidence rate of 4-5 cm/year. There is a large urban population for whom this ongoing subsidence is a problem and hence there is a willingness to invest in subsidence monitoring.

2. Subsidence category

Ground water extraction.

3. Geographical extents and optimal ERS coverage

From previous surveys the extent of the subsidence is approximately:

Longitude:	100° 15' E -100° 42' E	(40 km)
Latitude:	13° 28' N -14° 03' N	(55 km)

Greater Bangkok is 7,758 km^2 with a population of 6m.

4. Socio-economic effects of subsidence

Structural damage has occurred to buildings that have deep foundations due to the differential settlement of the soil. Concerns over seawater intrusions into groundwater.

5. Customer / contact

Rob Schumann, Asian Institute of Technology E-mail: esa@ait.ac.th

Eduardo Turcott, Geotechnical Research Centre, McGill University, Montreal ,Quebec, Canada
E-mail: EDUARDOT@civil.lan.mcgill.ca

Dr. Noppadol Phienwej, Asian Institute of Technology E-mail: noppadol@ait.ac.th

6. Subsidence rate/amount — *Rating: Medium*

The annual subsidence rate is 4-5 cm.
From 1991-1996 subsidence of about 4cm/per year has occurred at Samutsakorn and Samutprakarn stations (Bangkok Metropolitan), and 2cm/year at Bangkok Station.

7. Ground-truth available — *Rating: Medium*

The Royal Thai Survey Dept., and more recently the Asian Institute of Technology have maintained surveying every 6 months at 31 observation stations. A map of subsidence for the year 1992 has been received from the AIT.

8. Land cover — *Rating: Medium*

A large urban area, Bangkok is located in the Central plain of the Chao Phrya River on a low-lying area (elevations between 0.5 and 1.5m). The sedimentary deposits on which Bangkok is built are several hundred metres thick.

9. ERS Data availability and status — *Rating: Low*

No suitable ascending pairs available.
Descending: 3 pairs with perpendicular baselines less than 50m and a temporal separation greater than a year.

Receiving Station: Chung-Li

10. DEM availability

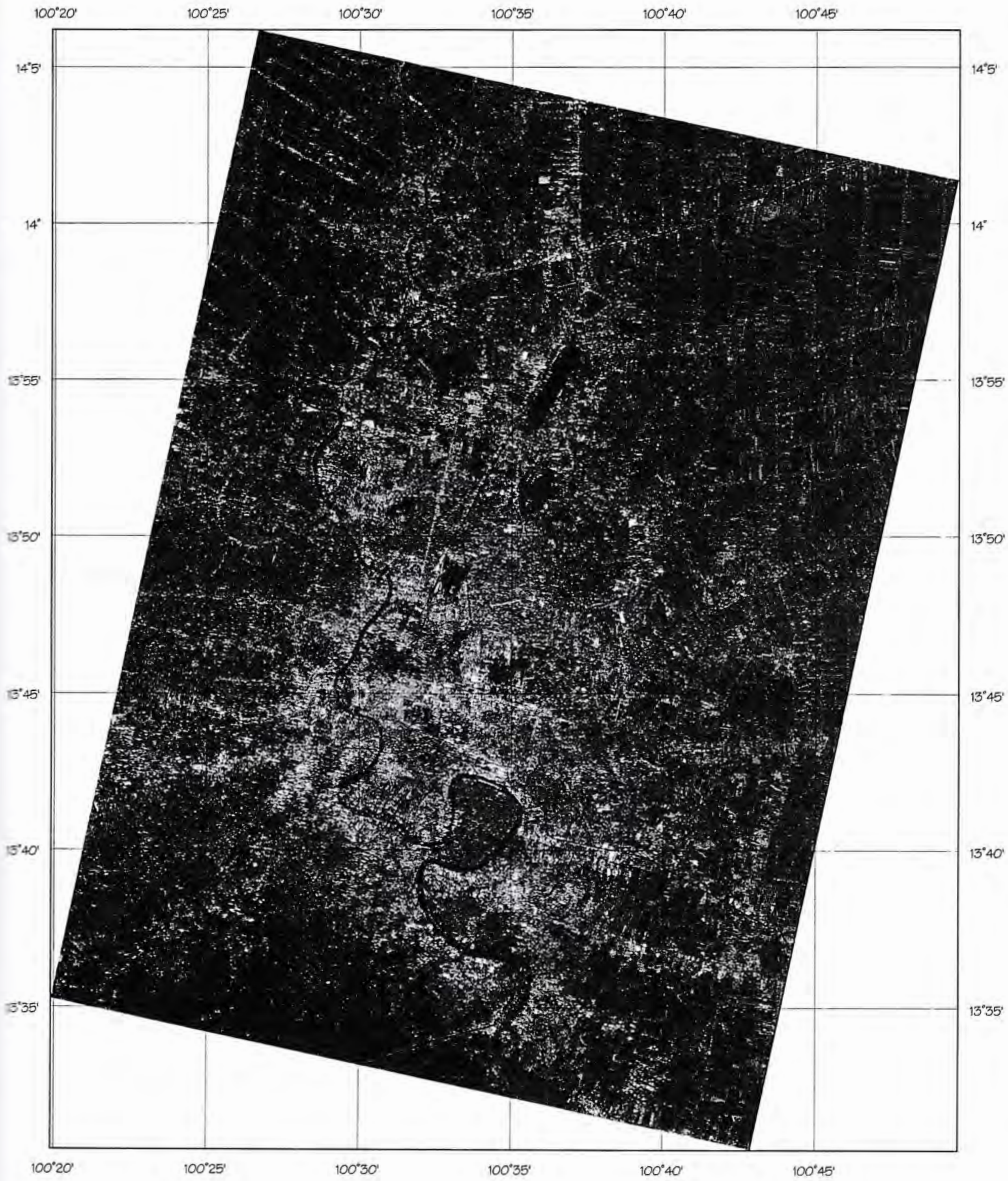
- GTOPO-30 coarse 1km resolution DEM of variable quality held in-house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in-house yet.
- Tandem InSAR.

11. Processing status

Two interferograms produced.

Radar amplitude image for the Bangkok area

ERS-2 scene date: 1 August 1993



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0 5 10 15 20 25 km

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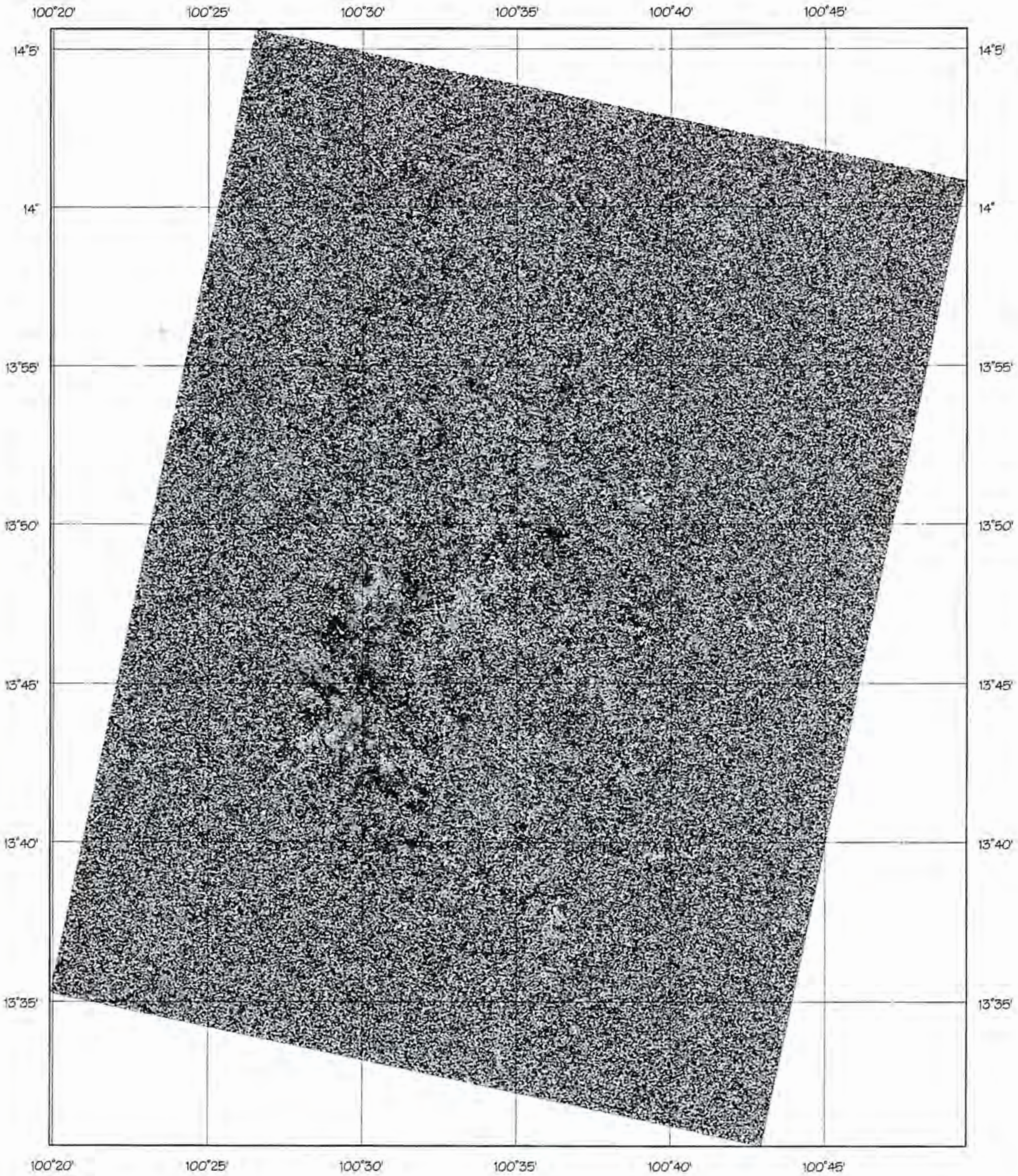
Interferogram for the Bangkok area

ERS scene dates: 1 August 1993 & 21 February 1996
Temporal separation: 2 years 6 months
Perpendicular baseline: 190 m
Altitude of ambiguity: 49.56 m



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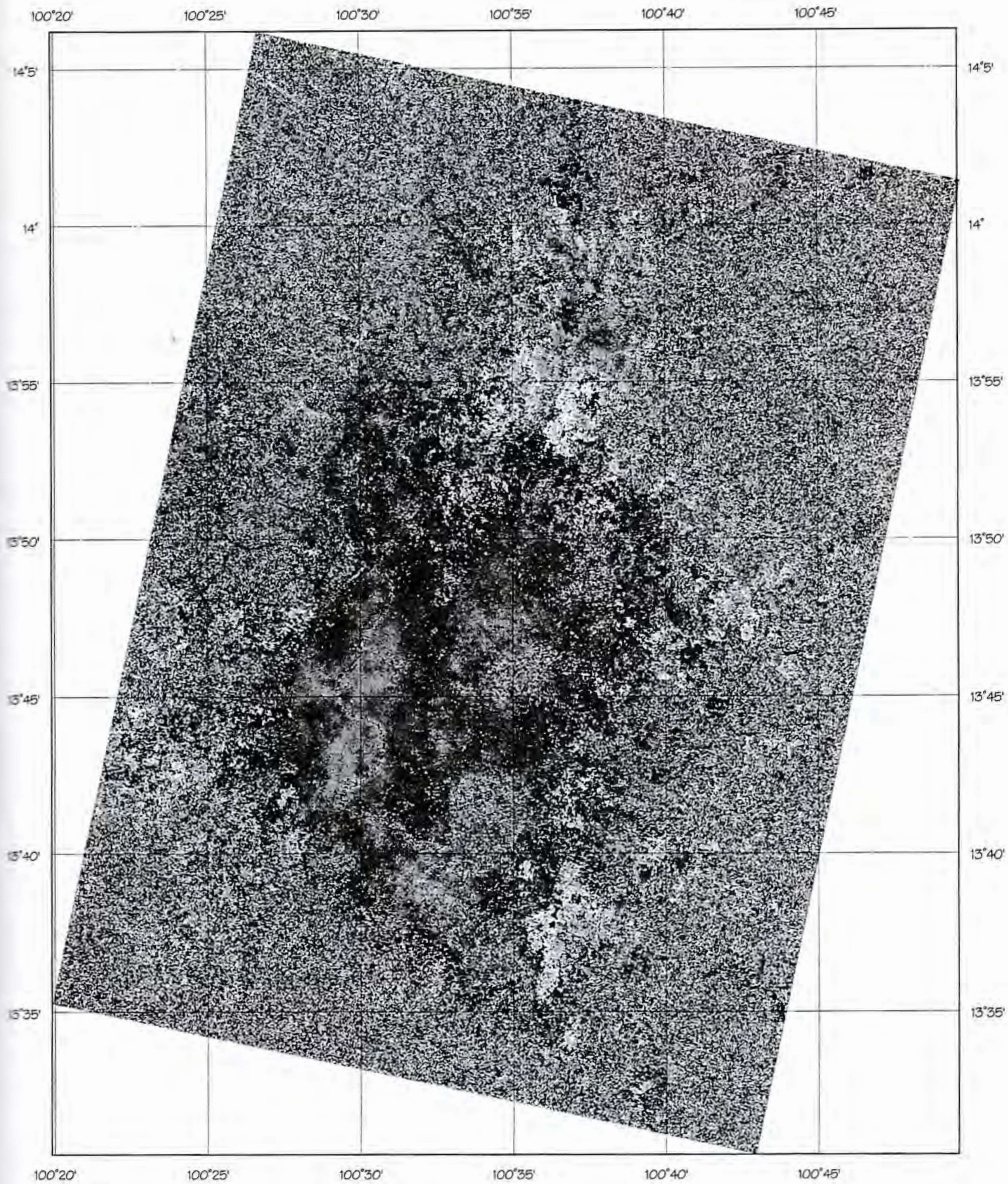
Interferogram for the Bangkok area

ERS-2 scene dates: 21 February 1996 & 23 October 1996
Temporal separation: 8 months
Perpendicular baseline: 24.5 m
Altitude of ambiguity: 384.33 m



0 5 10 15 20 25 km

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SAR & InSAR Processing Summary Report	**Bangkok: BAN_1 & BAN_2**

1. **Image Acquisition Dates:**	1/8/93, 21/2/96
2. **Temporal Separation:**	2 years 6 months
3. **Processing Stage (1[int], 2[diff] or 3[full]):**	1
4. **DEM details, if used:**	none
(i) Type:	
(ii) Pixel size:	
(iii) Accuracy – Planimetric & Vertical:	
5. **SLC Processing:**	
(i) Scene centre lat/long:	13° 47' 49" N, 100° 34' 41" E
(ii) Full- (or sub-) scene Range × Azimuth extents:	43.0 km × 58.4 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	Low coherence
6. **Ground-range PRI (Amplitude Image) Processing:**	
(i) Scene centre lat/long:	13° 48' 20" N,100° 34' 48" E
(ii) Full- (or sub-) scene Range × Azimuth extents:	48.5 km × 53.6 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	N
7. **InSAR Processing**	
(i) Interferogram or DEM-orthorectified Differential:	Interferogram
(ii) Perpendicular Baseline:	
(a) Nominal:	172 m
(b) Derived from Precise State Vectors:	189.5 m
(iii) Altitude of Ambiguity:	49.69 m
(iv) Range × Azimuth extents:	43.0 km × 58.4 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. **Coherence Map Parameters**	
(i) Mean:	17.55
(ii) Standard Deviation:	12.21

9. Analysis/Interpretation of Results

Figure 1

Radar amplitude image for 01-Aug-93

Figure 2

ERS interferogram, data acquired 01-Aug-93 and 21-Feb-96
Temporal separation: 2 years 6 months
Baseline: 190 m
Altitude of ambiguity: 50 m

Figure 3

ERS interferogram, data acquired 21-Feb-96 and 25-Oct-96
Temporal separation: 8 months
Baseline: 24.5 m
Altitude of ambiguity: 384 m

Two interferometric data sets have been acquired and analysed covering Bangkok. The data sets have temporal separations of approximately 8 months and 2.5 years.

Bangkok is known to suffer from systematic subsidence, and ground truth is available from a survey conducted in 1992. This site was consequently of some interest; to see whether the interferometric phase variations were consistent with ground based measurements.

The coherence levels for the 8-month separation data sets are good over the urban area and a good quality interferogram (figure 3) has been generated. The coherence levels for the 2.5 year pair are unfortunately sufficiently poor to preclude any interpretation; the reason for the poor coherence is not known, but is likely to be weather related.

No digital elevation model was available to support data processing; however the topography is predominantly flat, and the baseline for the first pair is sufficiently narrow that at most a few degrees of phase variation is related to topography. The georeference provided by the grid overlay is accurate to the order of 150 metres.

It is difficult to come to any firm conclusion from the interferometric phase variations of figure 3. Within the urban area variations of order ½ a phase cycle (equivalent to 1.5 cm of heave/subsidence) can be observed, with a possible indication of greater movement towards the edge of the urban area to the East, West and North, where the data becomes incoherent. This is consistent with local ground measurements made 4 years prior to the ERS acquisitions of figure 3, which have indicated a widespread pattern of annual subsidence in the city centre with rates of order 2-3 cm, increasing to the East and West and around the airport to the North. However, the magnitude of the phase variations is comparable to that induced by atmospheric and other sources of error, and at around the sensitivity of the technique - the eight month temporal separation of the 21-Feb-96 and 25-Oct-96 acquisitions is too short for confident mapping of subsidence at these subsidence rates.

10. Conclusions/Recommendations

It would be worthwhile to examine a further interferometric pair with an extended temporal separation; the poor coherence of the 01-Aug-93 and 21-Feb-96 data sets is not necessarily indicative of a coherence time limit over tropical urban areas, and there is no good reason to suppose that dry season acquisitions with a 4 year separation would provide inadequate coherence.

SAR & InSAR Processing Summary Report — Bangkok: BAN_2 & BAN_3

1. Image Acquisition Dates:	21/2/96, 23/10/96
2. Temporal Separation:	8 months
3. Processing Stage (1[int], 2[diff] or 3[full]):	1
4. DEM details, if used:	none
(i) Type:	
(ii) Pixel size:	
(iii) Accuracy – Planimetric & Vertical:	
5. SLC Processing:	
(i) Scene centre lat/long:	13° 47' 49" N, 100° 34' 41" E
(ii) Full- (or sub-) scene Range × Azimuth extents:	43.0 km × 58.4 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	Low coherence
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	13° 48' 20" N,100° 34' 48" E
(ii) Full- (or sub-) scene Range × Azimuth extents:	48.5 km × 53.6 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	N
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	Interferogram
(ii) Perpendicular Baseline:	
(a) Nominal:	23 m
(b) Derived from Precise State Vectors:	24.5 m
(iii) Altitude of Ambiguity:	384.3 m
(iv) Range × Azimuth extents:	43.0 km × 58.4 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	23.82
(ii) Standard Deviation:	18.78

9. Analysis/Interpretation of Results

Figure 1

Radar amplitude image for 01-Aug-93

Figure 2

ERS interferogram, data acquired 01-Aug-93 and 21-Feb-96
Temporal separation: 2 years 6 months
Baseline: 190 m
Altitude of ambiguity: 50 m

Figure 3

ERS interferogram, data acquired 21-Feb-96 and 25-Oct-96
Temporal separation: 8 months
Baseline: 24.5 m
Altitude of ambiguity: 384 m

Two interferometric data sets have been acquired and analysed covering Bangkok. The data sets have temporal separations of approximately 8 months and 2.5 years.

Bangkok is known to suffer from systematic subsidence, and ground truth is available from a survey conducted in 1992. This site was consequently of some interest; to see whether the interferometric phase variations were consistent with ground based measurements.

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10. Conclusions/Recommendations

It would be worthwhile to examine a further interferometric pair with an extended temporal separation; the poor coherence of the 01-Aug-93 and 21-Feb-96 data sets is not necessarily indicative of a coherence time limit over tropical urban areas, and there is no good reason to suppose that dry season acquisitions with a 4 year separation would provide inadequate coherence.

London, UK **OVERALL RATING: 73%**

1. Marketability *Rating: Good*

Major city with a recognised subsidence problem. RMS (formerly CARtograph) are an established customer of NPA.

2. Subsidence category

Clay shrink swell.

3. Geographical extents and optimal ERS coverage

The extents of Greater London are approximately:

Longitude:	0° 27' E - 0° 17' W	(40 km)
Latitude:	51° 17' N - 51° 41' N	(40 km)

4. Socio-economic effects of subsidence

The majority of insurance claims for subsidence damage to property in the UK are for properties in the southeast. The cost of insurance claims for damage to property due to subsidence has increased year on year since 1994.

5. Customer / contact

RMS.

6. Subsidence rate/amount — Rating: Poor

Unknown.

7. Ground-truth available — Rating: Poor

None available.

8. Land cover — Rating: Good

Major urban area, surrounded by fairly flat arable land.

9. ERS Data availability and status — Rating: High

No suitable ascending frames.
Descending: More than 10 pairs with perpendicular baselines less than 50m and a temporal separation greater than a year.

Receiving station: West Freugh, Fucino

10. DEM availability

- EuroDEM 100 m × 100m grid with 30m accuracy held in-house.
- GTOPO-30 coarse 1km resolution DEM of variable quality held in-house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in-house yet.
- Tandem InSAR.

11. Processing status

Two differential interferograms produced.

Radar amplitude image for the London area

ERS scene date: 9 February 1993

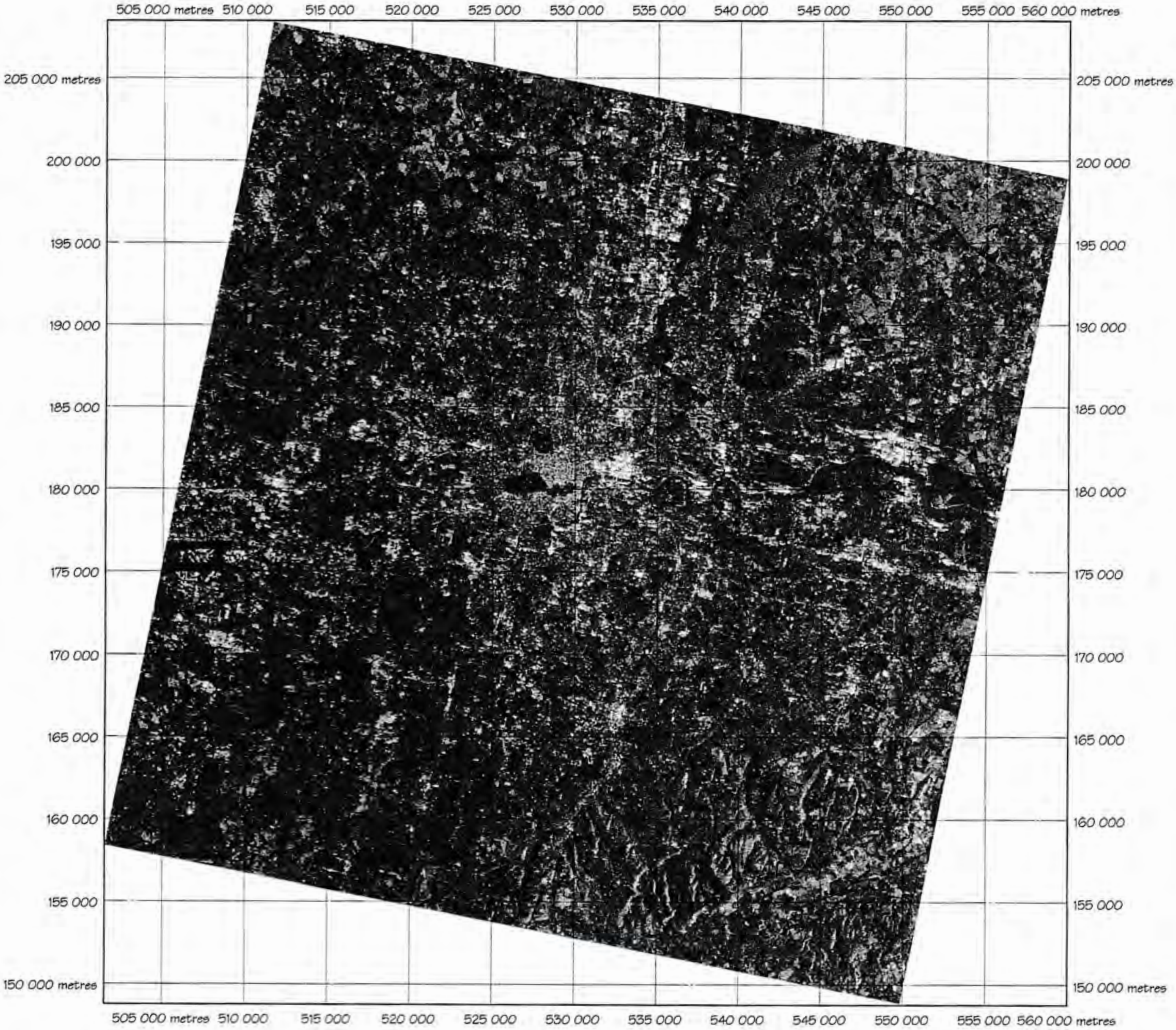

Image Copyright NPA 1998, ESA 1993

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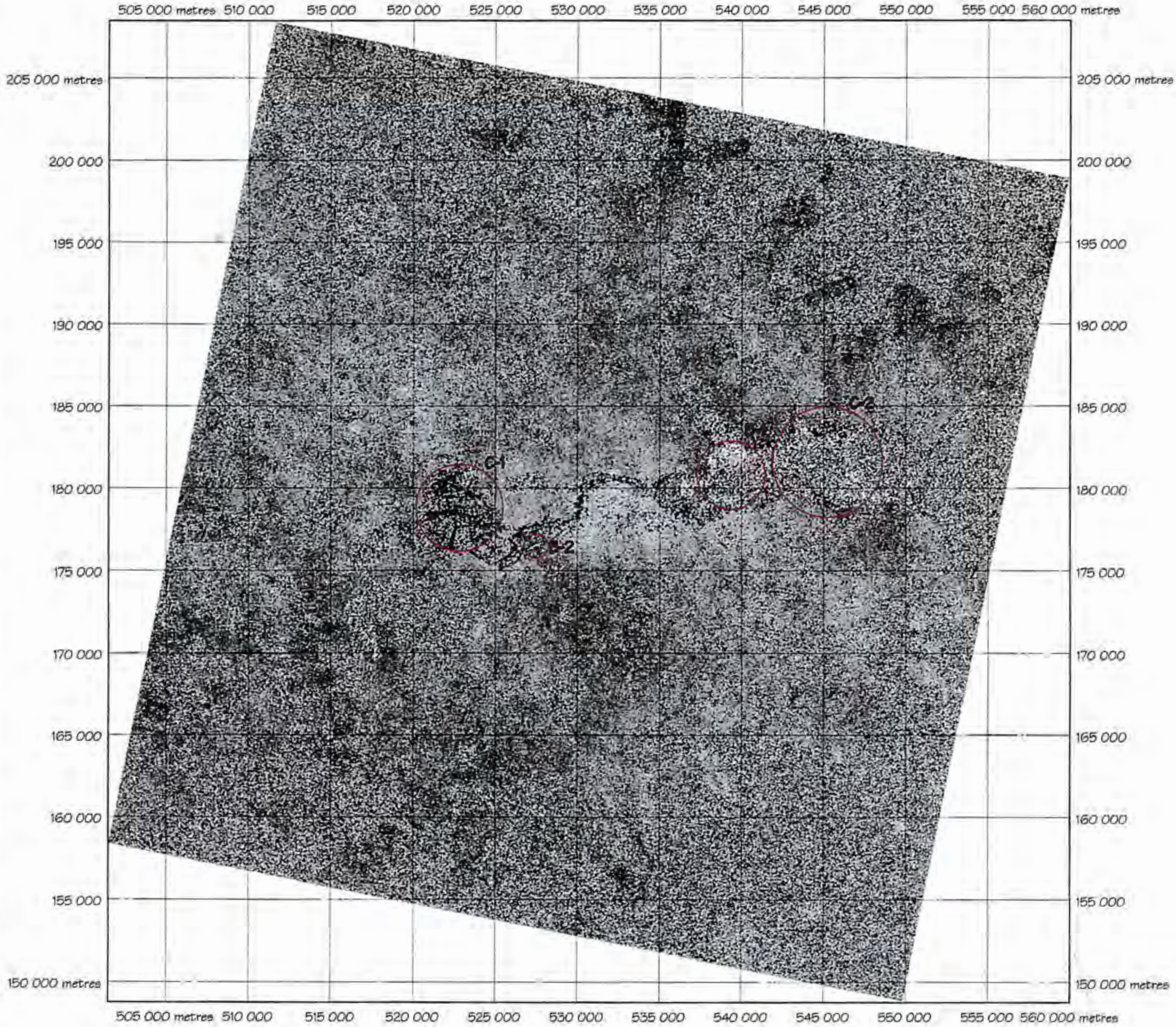
Differential interferogram for the London area

ERS scene dates: 9 February 1993 & 1 September 1995
Temporal separation: 2 years 7 months
Perpendicular baseline: 87.4 m
Altitude of ambiguity: 107.7 m

Rings indicate fringe features in this image



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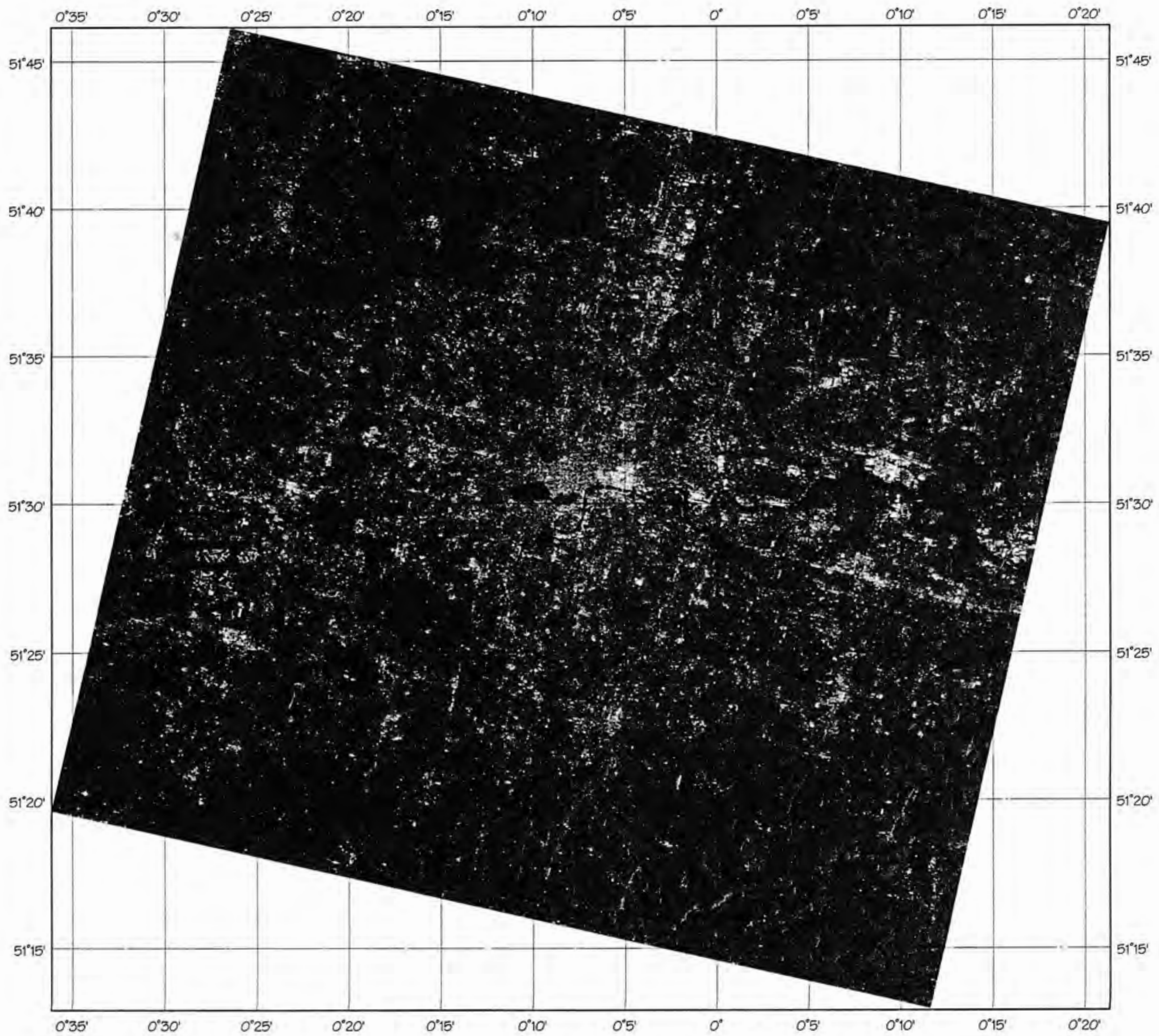
Radar amplitude image for the London area

ERS scene date: 27 June 1997



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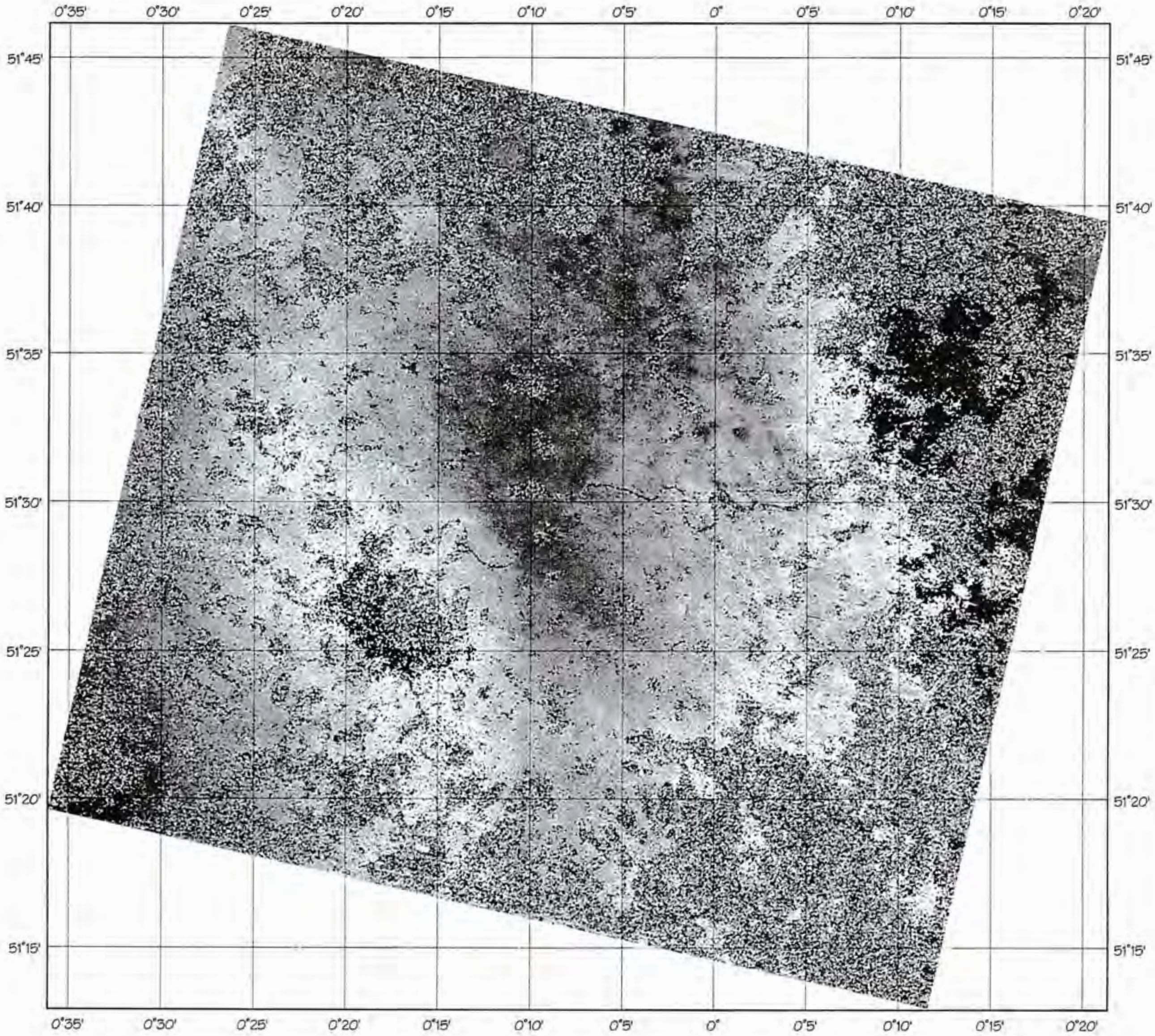
Differential interferogram for the London area

ERS scene dates: 27 June 1997 & 19 December 1997
Temporal separation: 6 months
Perpendicular baseline: 10.9 m
Altitude of ambiguity: 863.9 m



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SAR & InSAR Processing Summary Report **London: LON_5 & LON_6**

1. Image Acquisition Dates:	9/2/93, 1/9/95
2. Temporal Separation:	2 years 7 months
3. Processing Stage (1[int], 2[diff] or 3[full]):	2
4. DEM details, if used:	
(i) Type:	InSAR DEM generated from a tandem pair, with gaps filled in from a 50 m DEM
(ii) Pixel size:	50 m
(iii) Accuracy – Planimetric & Vertical:	50 m, 5m
5. SLC Processing:	
(i) Scene centre lat/long:	51° 30' 00"° N, 0° 06' 29" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	50.40 km × 60.20 km
(iii) Range & Azimuth pixel size:	12.50 m, 3.13 m
(iv) Reason (if applicable) for sub-scene processing:	extract over London
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	51° 29' 37" N, 0° 07' 09" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	51.2 km × 60.8 km
(iii) Range & Azimuth pixel size:	12.5 m, 12.5 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	88 m
(b) Derived from Precise State Vectors:	87.75 m
(iii) Altitude of Ambiguity:	107.70 m
(iv) Range × Azimuth extents:	50.2 km × 46.6 km
(v) Range & Azimuth pixel size:	16, 4
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	21.98
(ii) Standard Deviation:	14.95

9. Analysis/Interpretation of Results

These interferometric acquisitions of London were originally processed using an external DEM in 1997, resulting in a differential interferogram (not included here). The most significant feature in this first interferogram was a 12 km^2 area of East London around Canning town, which had subsided by around 1.5 cm over the 2.5 year period. Overall the interferogram exhibited some degree of phase variation over the metropolitan area, but it was unclear as to whether this was caused by true ground movements, by errors in the (relatively coarse) DEM or by ionospheric effects.

In view of the relatively large baseline (and consequent sensitivity to DEM errors) it was decided to generate a higher resolution DEM interferometrically, using a 'tandem' pair of ERS-1/ERS-2 acquisitions, and to reprocess the differential interferogram. The refined DEM was generated by a differential technique using the existing DEM as a starting point, with the phase variations of the resulting differential interferogram interpreted as height corrections. The baseline of the most readily available tandem pair was around 190 metres, and the refined DEM had a spatial resolution of order 40 metres with a vertical accuracy of a few metres in the regions of highest coherence, with its accuracy decreasing with decreasing coherence.

A number of differences are apparent:

- In general, the phase of the interferogram is more uniform than the first, with little evidence supporting clay related swelling or subsidence over the acquisition interval. The reduction in the variability of the phase of the differential interferogram is thought to occur because the interferometrically derived DEM measures the envelope of the scattering surface rather than the nominal ground surface.
- The quality is degraded relative to the previous interferogram in areas of low coherence. This is particularly evident when the regions close to the track of the Thames are inspected. The use of an interferometrically derived DEM inherently adds noise to a differential interferogram - to a first approximation, phase noise in the tandem interferogram is added to that of the differential product in inverse proportion to the respective InSAR baselines and in this instance there is a relatively narrow baseline for the tandem pair and a relatively high baseline for the differential acquisitions. The Canning town feature is much less clear relative to the previous interferogram as a consequence.
- An increased confidence in the DEM quality has allowed some other some other surface movement activity to be identified:

    1. The railway ENE of Clapham Junction has subsided by of order 1 cm.
    2. There is some evidence of subsidence in the Hammersmith area and in the Thames estuary East of Greenwich.

10. Conclusions/Recommendations

Category	Label	OS Grid ref.	Comments
2 class B features	B1	538000E 182000N	Canning Town
	B2	527500E 177000N	Clapham Junction
2 class C features	C1	522500E 177500N	Hammersmith
	C2	547000E 182000N	Thames Estuary

Categories: A *Definite, large-scale subsidence*

B *Probable/smaller-scale subsidence over a larger area*

C *Possible subsidence over a larger area*

D *Processing artefact/Feature of interest*

For further studies of London we would suggest acquiring an additional pair with a shorter temporal separation (6 months).

SAR & InSAR Processing Summary Report **London: LON_9 & LON_10**

1. Image Acquisition Dates:	27/6/97, 19/12/97
2. Temporal Separation:	6 months
3. Processing Stage (1[int], 2[diff] or 3[full]):	2
4. DEM details, if used:	
(i) Type:	InSAR DEM generated from a tandem pair, with gaps filled in from a 50 m DEM
(ii) Pixel size:	50 m
(iii) Accuracy – Planimetric & Vertical:	50 m, 5 m
5. SLC Processing:	
(i) Scene centre lat/long:	51° 14' 17" N, 0° 03' 18" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.4 km × 106.5 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	51° 29' 33" N, 0° 07' 24" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	56.6 km × 50.5 km
(iii) Range & Azimuth pixel size:	16 m, 16 m
(iv) Number of Looks:	4
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	6 m
(b) Derived from Precise State Vectors:	10.9 m
(iii) Altitude of Ambiguity:	863.9 m
(iv) Range × Azimuth extents:	56.6 km × 50.6 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	28.41
(ii) Standard Deviation:	20.22

9. Analysis/Interpretation of Results

This is the third differential interferogram processed over London. The interferogram exhibits good coherence over the urban areas, with little obvious atmospheric phase noise. The data has however been corrected for linear phase trends in both range and along track directions; these trends are thought to arise from large-scale variation in the refractive characteristics of the atmosphere.

At a small scale only a very few localised variations in differential phase can be observed, and in general the phase over the urban areas is convincingly smooth.

On a large scale a slight non-linear curvature to the differential phase over the scene is apparent, of a magnitude of order ½ a phase cycle. This might be indicative of some large-scale phenomenon, but this is thought unlikely; it has been necessary to correct the data for empirically determined linear trends and there is every reason to suppose that the residual phase curvature arises from the same underlying cause.

10. Conclusions/Recommendations

It is very difficult to reconcile such a stable phase image with London's reputation for damage to housing through clay-related shrinkage and swelling.

Selby, UK — OVERALL RATING: 67%

1. Marketability — *Rating: Medium*

Possible interest from the Coal Authority.

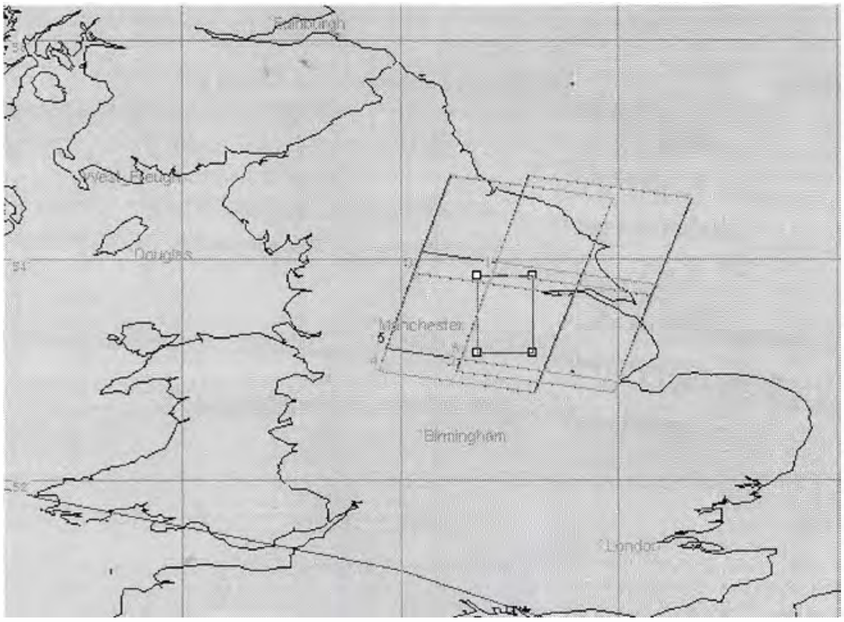
2. Subsidence category

Coal mining.

3. Geographical extents and optimal ERS coverage

The extents of the area with subsidence problems from previous surveys are:

Longitude:	0° 47' W - 1° 18' W	(30 km)
Latitude:	53° 9' N - 53° 51' N	(80 km)



4. Socio-economic effects of subsidence

Unknown.

5. Customer / contact

Coal Authority – Keith Leighfield.

6. Subsidence rate/amount — *Rating: High*

Subsidence rates as high as 50 mm in one month were observed in previous work over the Selby area.

7. Ground-truth availability *Rating: Medium*

Extensive ground-truth data available: Maps of mined areas, dates of mining activity, subsidence measurements from surveys and subsidence predictions.

8. Land cover *Rating: Poor*

Flat river plain with the majority of the land below 10m covered in arable farm land with scattered urban areas.

9. ERS Data availability and status *Rating: Medium*

Ascending and descending pairs available.
Descending scenes have a preferable footprint.
More than 15 pairs with perpendicular baselines less than 50m and a temporal separation greater than a year are available.

Receiving station: Fucino

10. DEM availability

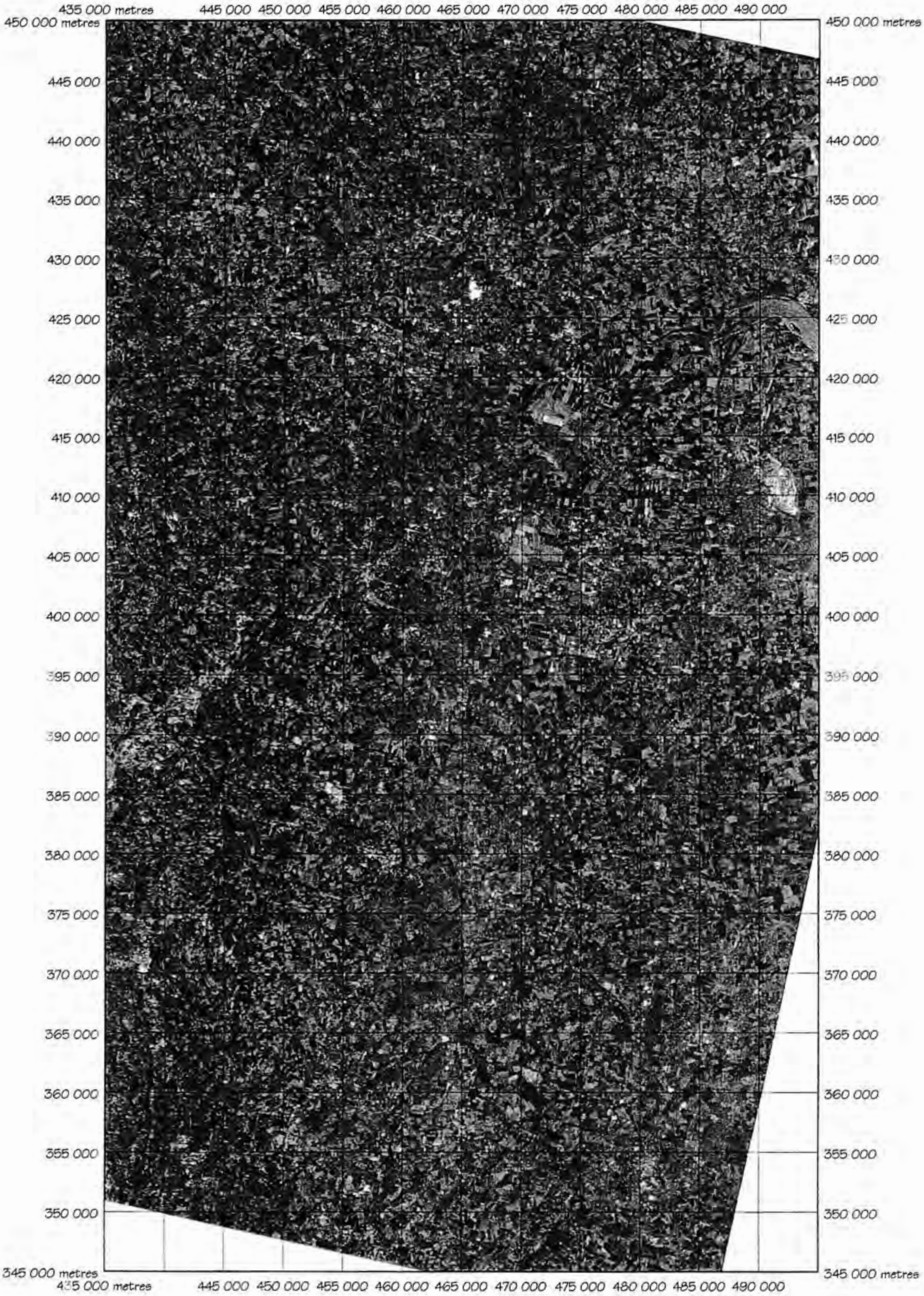
- EuroDEM 100 m × 100m grid with 30m accuracy held in-house.
- GTOPO-30 coarse 1km resolution DEM of variable quality held in-house.
- Russian Mapping 40m resolution approx. £600 for 1° E-W and 40' N-S
  20m resolution approx. £600 for 30' E-W and 30' N-S (limited coverage).
- Stereo SPOT, cost of about £6600 for 60 km × 60 km.
- Stereo Radarsat 30-40m resolution, but not tested in-house yet.
- Tandem InSAR.

11. Processing status

Two differential interferograms produced.

Radar amplitude image for the Selby area and extending south

ERS scene date: 21 July 1993



0 5 10 15 20 25 km

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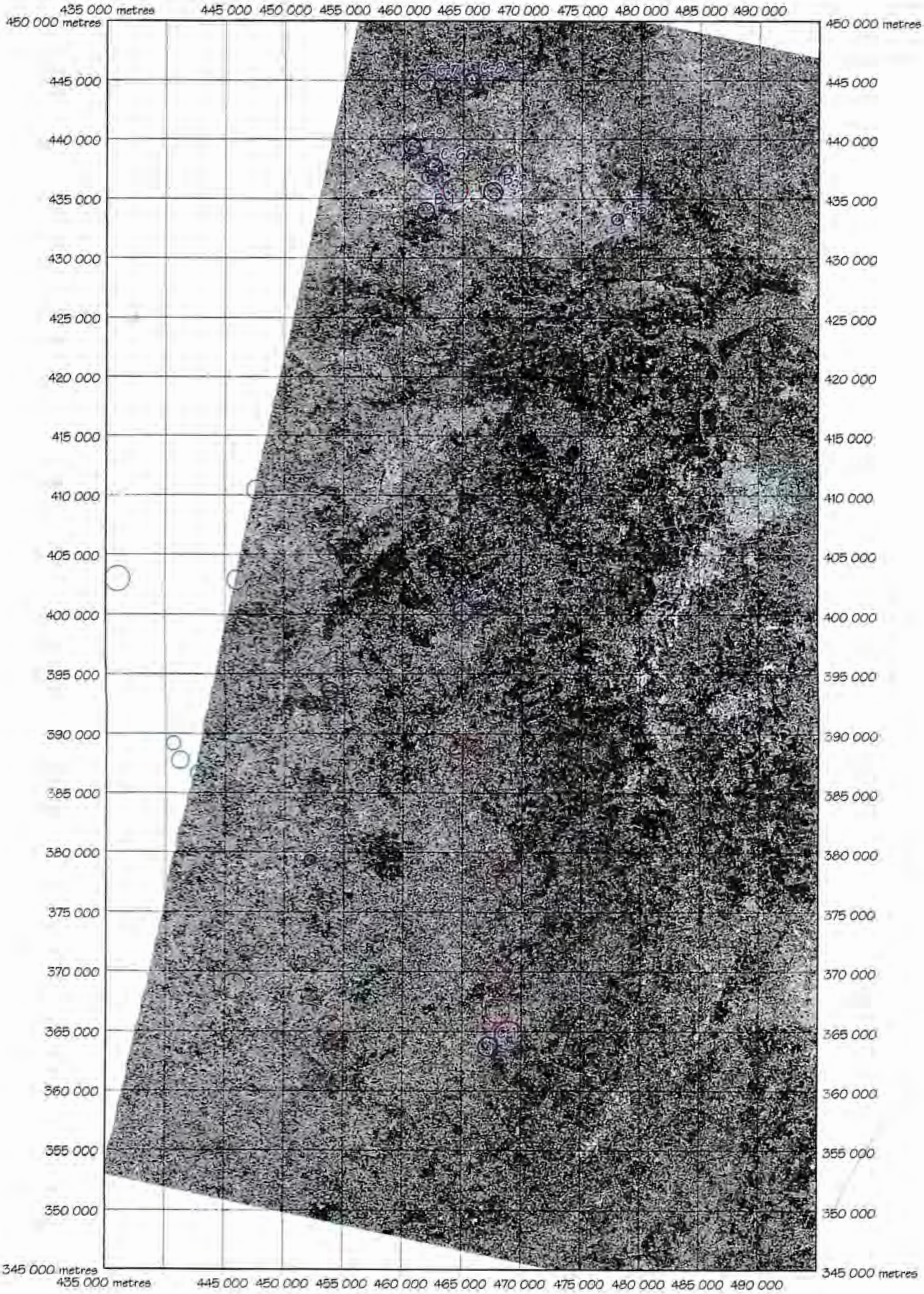
Differential interferogram for the Selby area and extending south

ERS scene dates: 6 January 1997 & 17 March 1997
Temporal separation: 70 days
Perpendicular baseline: 191.2 m
Altitude of ambiguity: 49.3 m

Blue rings: fringe features in this image
Green rings: fringe features in the 21 July-25 August 1993 interferogram (35 days)
Red rings: fringe features in the 12 February-19 March 1993 interferogram (35 days)



0 5 10 15 20 25 km

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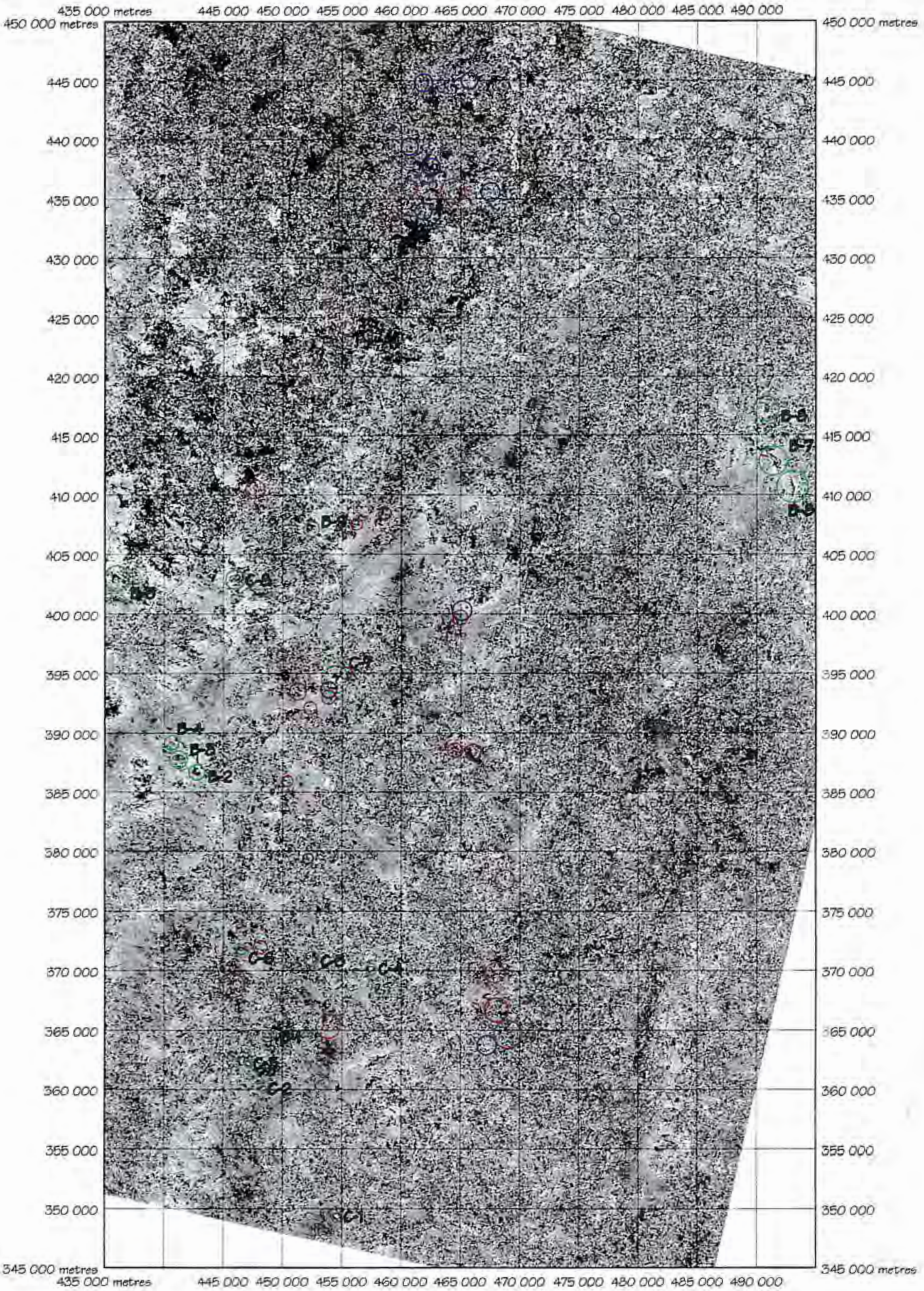
Differential interferogram for the Selby area and extending south

ERS scene dates: 21 July 1993 & 25 August 1993
Temporal separation: 35 days
Perpendicular baseline: 209.3 m
Altitude of ambiguity: 45.0 m

Green rings: fringe features in this image
Blue rings: fringe features in the 6 January-17 March interferogram (70 days)
Red rings: fringe features in the 12 February-19 March 1993 interferogram (35 days)



NPA SATELLITE MAPPING

esa european space agency

0 5 10 15 20 25 km

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SAR & InSAR Processing Summary Report **Selby: SEL_3 & SEL_4**

1. Image Acquisition Dates:	6/1/97, 17/3/97
2. Temporal Separation:	70 days
3. Processing Stage (1[int], 2[diff] or 3[full]):	2
4. DEM details, if used:	
(i) Type:	50 m DEM
(ii) Pixel size:	50 m
(iii) Accuracy – Planimetric & Vertical:	2.5 m, 2.5 m
5. SLC Processing:	
(i) Scene centre lat/long:	53° 25' 19" N, 0° 34' 34" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	100.35 km × 106.5 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	53° 25'18" N, 0° 35' 39" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	102.4 km × 107.2 km
(iii) Range & Azimuth pixel size:	16 m, 12.5 m
(iv) Number of Looks:	3
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	191 m
(b) Derived from Precise State Vectors:	191.2 m
(iii) Altitude of Ambiguity:	40.3 m
(iv) Range × Azimuth extents:	100.4 km × 106.5 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	3, 12
8. Coherence Map Parameters	
(i) Mean:	26.55
(ii) Standard Deviation:	14.41

9. Analysis/Interpretation of Results

Differential interferograms covering the Selby coal-mining region in the UK are presented for summer 1993 and winter 1997. These data sets complement a very revealing high coherence pair of acquisitions previously analysed covering the 35-day period Feb to March 1993.

With the exception of the urban areas the coherence levels on these data sets is relatively poor, and the relatively large baselines make the analyses sensitive to DEM errors - with a 20 metre DEM error corresponding to a 180 degree phase error. The noticeably greater variability of phase in the summer interferogram is attributed to ionospheric effects.

The characteristics of summer and winter interferogram are markedly different as a result of seasonal effects. In the winter pair the Humber estuary and its tributaries are clearly evident as boundaries of low coherence; on the summer pair only the urban areas have a stable phase response. This difference is presumed to arise as a consequence of increased vegetation cover during the summer months. A number of linear features can be observed on both interferograms; these correspond to main railway lines.

Identification of surface subsidence activity is made very difficult because of the low coherence and the general degree of variation in the differential phase. However because a common DEM has been used with both pairs of acquisitions effects associated with DEM errors can be identified to a degree.

A number of localised subsidence events have been identified from inspection of the interferograms; in general there is little or no intersection between events identified on the Summer and Winter interferograms or between these events and those clearly evident on the 1993 Feb/Mar analysis. This may be of significance, in that the majority of events are related to mining activity, and the lack of spatial intersection may suggest that (small) mining related subsidence occurs through a stress relaxation mechanism, but is not usually a continuing process.

In addition to mining related surface movement, some clear and extended settlement has occurred within the Scunthorpe urban area over the summer of 1993 with different spatial characteristics to other mining related activity, which might deserve further investigation.

10. Conclusions/Recommendations

Winter 1997

Category	Label	OS Grid ref.	Comments
2 class B features	B1	463000E 434000N	~5cm
	B2	467500E 436000N	~5cm
9 class C features	C1	468000E 363000N	
	C2	453000E 379000N	
	C3	454000E 393500N	
	C4	465000E 401000N	
	C5	478000E 433000N	
	C6	465000E 438000N	
	C7	463000E 444500N	
	C8	466000E 445000N	
	C9	460000E 439000N	

Categories: A *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/Feature of interest*

We recommend acquiring another 35-day separation data set for the same period as the previous study of the Selby area but for another region of the UK suffering from mining related subsidence.

SAR & InSAR Processing **Selby: SEL_5 & SEL_6**
Summary Report

1. Image Acquisition Dates:	21/7/93, 25/8/93
2. Temporal Separation:	35 days
3. Processing Stage (1[int], 2[diff] or 3[full]):	2
4. DEM details, if used:	
(i) Type:	50 m DEM
(ii) Pixel size:	50 m
(iii) Accuracy – Planimetric & Vertical:	2.5 m, 2.5 m
5. SLC Processing:	
(i) Scene centre lat/long:	53° 30' 11" N, 1° 15' 47" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	99.3 km × 106.5 km
(iii) Range & Azimuth pixel size:	16 m, 4 m
(iv) Reason (if applicable) for sub-scene processing:	
6. Ground-range PRI (Amplitude Image) Processing:	
(i) Scene centre lat/long:	53° 30' 54" N, 1° 17' 4" W
(ii) Full- (or sub-) scene Range × Azimuth extents:	102.4 km × 107.2 km
(iii) Range & Azimuth pixel size:	16 m, 12.5 m
(iv) Number of Looks:	3
(v) DEM-orthorectified (Y/N):	Y
7. InSAR Processing	
(i) Interferogram or DEM-orthorectified Differential:	DEM-orthorectified Differential
(ii) Perpendicular Baseline:	
(a) Nominal:	200 m
(b) Derived from Precise State Vectors:	209.3 m
(iii) Altitude of Ambiguity:	45.0 m
(iv) Range × Azimuth extents:	99.3 km × 106.5 km
(v) Range & Azimuth pixel size:	16 m, 16 m
(vi) Range & Azimuth pixel smoothing:	5, 20
8. Coherence Map Parameters	
(i) Mean:	22.46
(ii) Standard Deviation:	15.76

9. Analysis/Interpretation of Results

Differential interferograms covering the Selby coal-mining region in the UK are presented for summer 1993 and winter 1997. These data sets complement a very revealing high coherence pair of acquisitions previously analysed covering the 35-day period Feb to March 1993.

With the exception of the urban areas the coherence levels on these data sets is relatively poor, and the relatively large baselines make the analyses sensitive to DEM errors - with a 20 metre DEM error corresponding to a 180 degree phase error. The noticeably greater variability of phase in the summer interferogram is attributed to ionospheric effects.

The characteristics of summer and winter interferogram are markedly different as a result of seasonal effects. In the winter pair the Humber estuary and its tributaries are clearly evident as boundaries of low coherence; on the summer pair only the urban areas have a stable phase response. This difference is presumed to arise as a consequence of increased vegetation cover during the summer months. A number of linear features can be observed on both interferograms; these correspond to main railway lines.

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In addition to mining related surface movement, some clear and extended settlement has occurred within the Scunthorpe urban area over the summer of 1993 with different spatial characteristics to other mining related activity, which might deserve further investigation.

10. Conclusions/Recommendations

Summer 1993

All surface displacements identified have a magnitude of order 1-2.5 cm

Category	Label	OS Grid ref.
9 class B features	B1	449000E 364500N
	B2	443000E 387000N
	B3	441500E 388000N
	B4	441000E 389000N
	B5	436000E 403000N
	B6	493000E 411000N
	B7	492000E 413000N
	B8	491000E 417000N
	B9	455000E 407500N
8 class C features	C1	454500E 349000N
	C2	448000E 360000N
	C3	447000E 364000N
	C4	457500E 370000N
	C5	455000E 372000N
	C6	447000E 372000N
	C7	455000E 395000N
	C8	446000E 403000N

Categories: A *Definite, large-scale subsidence*
B *Probable/smaller-scale subsidence over a larger area*
C *Possible subsidence over a larger area*
D *Processing artefact/Feature of interest*

We recommend acquiring another 35-day separation data set for the same period as the previous study of the Selby area but for another region of the UK suffering from mining related subsidence.